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Title: Projecting Regional Climate Change and its Impacts in the Western U.S.

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Projecting Regional Climate Change and its Impacts in the Western U.S.

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Pacific Northwest National Laboratory

I-WEST SEMINAR SERIES
February 3, 2022

Outline

- Global warming increases extreme weather events
  - "We're experiencing new weather, because we've made a new climate." – Bulletin of American Meteorological Society, 2017
- Regional climate change in western U.S. – California as an example
  - Understanding the robust and non-robust changes projected by models
- Strategies and progress in DOE Energy Exascale Earth System Model (E3SM)
  - Advancing earth system modeling for actionable science

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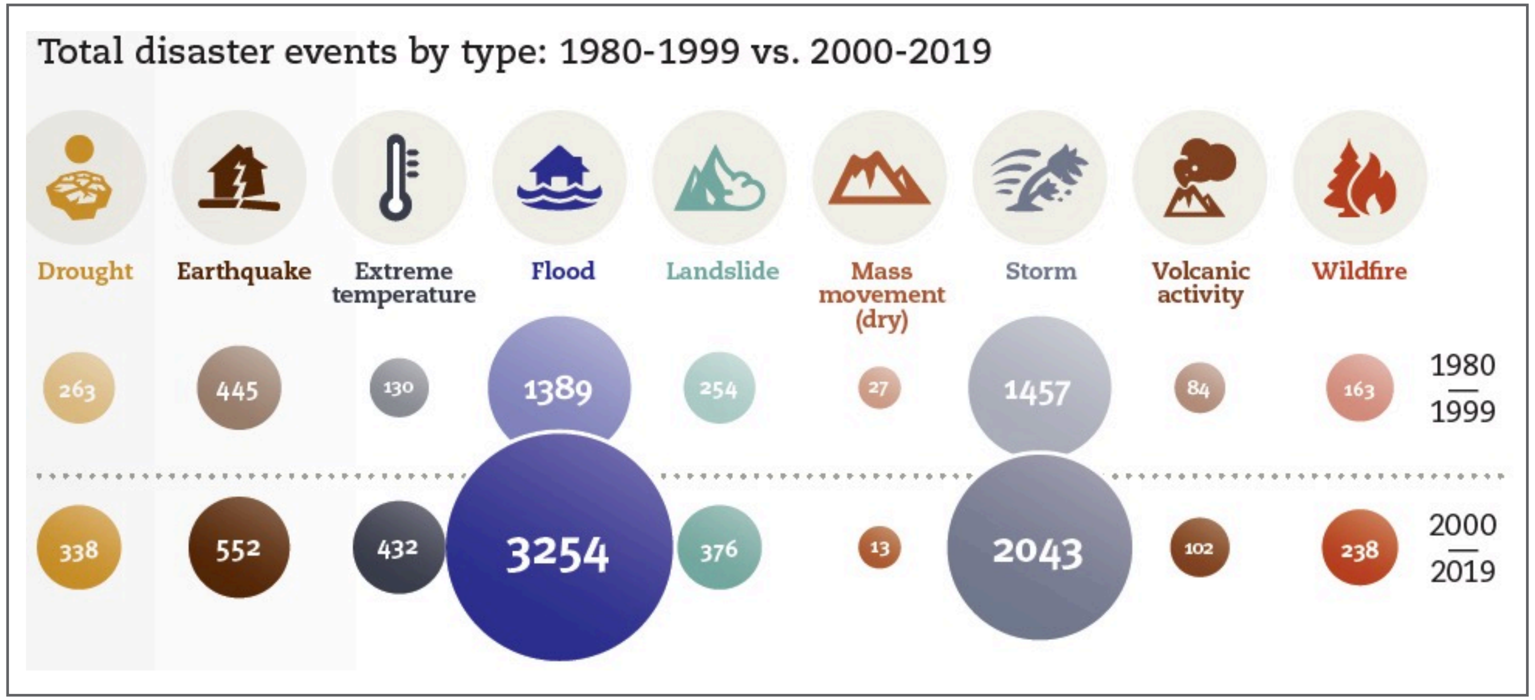
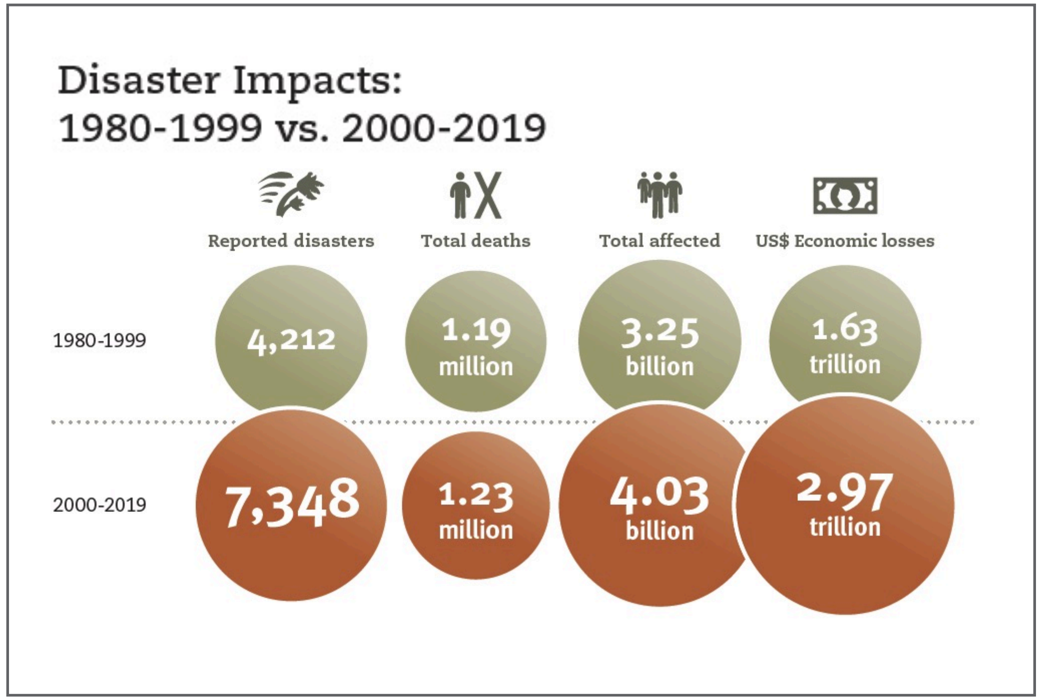
Extreme events have increased significantly in 2000-2019 compared to 1980-1999





(UN report 2020)

U.S. energy sector is vulnerable to extreme weather events

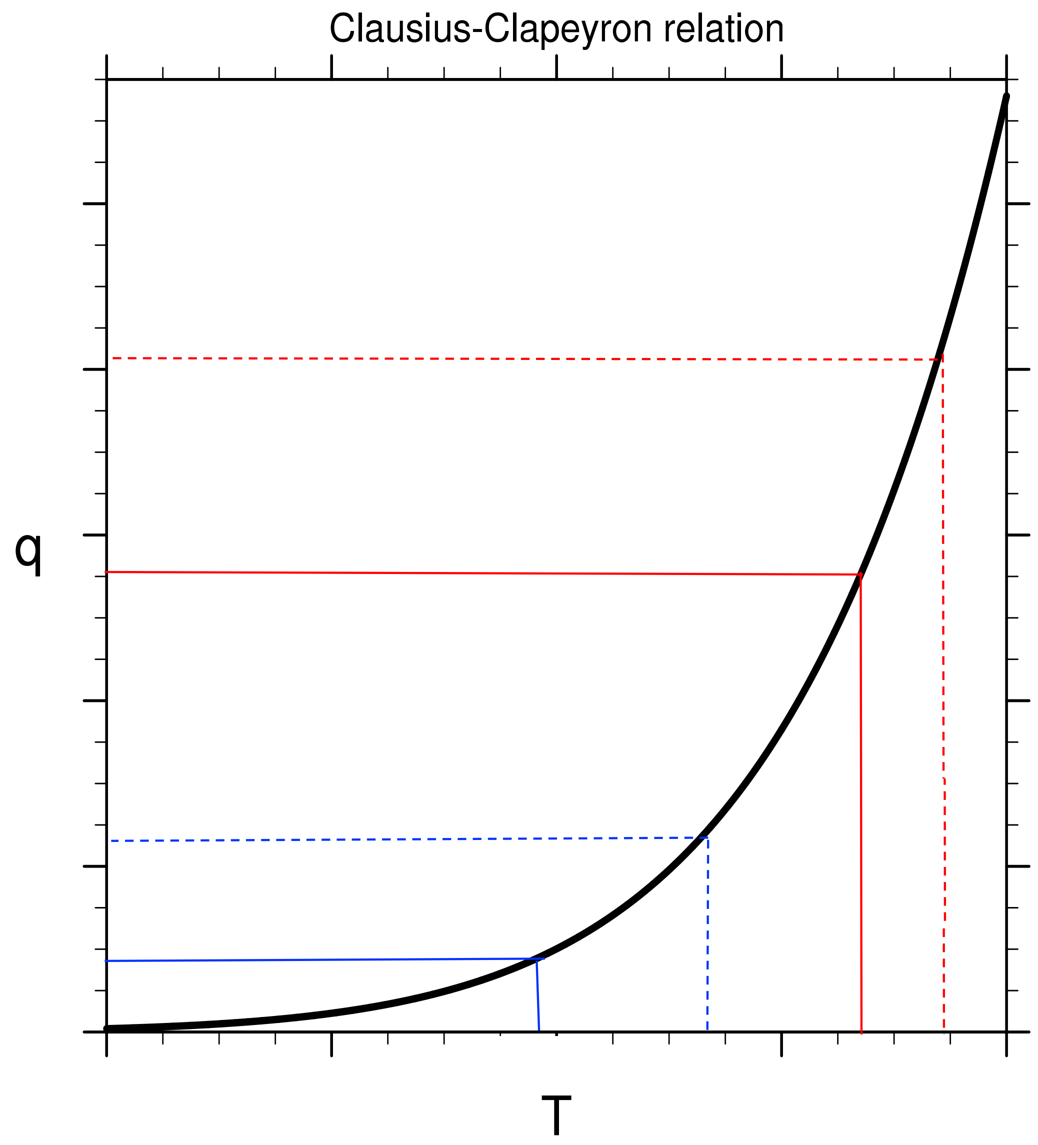
June 2012 derecho in West Virginia: Power transmission infrastructure damages exceeded $170 million

Hurricane Harvey in 2017 in Texas: Power outages affected more than quarter-million customers

June 2021 heat wave in US Northwest: Rolling blackouts amid heavy power demand

Why extreme weather events are expected to increase with global warming?

- Humidity increases with temperature at a nonlinear rate following the Clausius-Clapeyron relation
  - As a greenhouse gas, humidity amplifies warming by a factor of 1.5-2.0
  - As humidity increases with warming, so does latent heat release which drives tropical convection and atmospheric circulation
  - Increase in latent energy plays a major role in increase in weather extremes
- Surface equivalent potential temperature (thetae_sfc), an integrated metric of temperature and humidity, is a more comprehensive metric of global warming than surface air temperature (SAT), especially for weather extremes

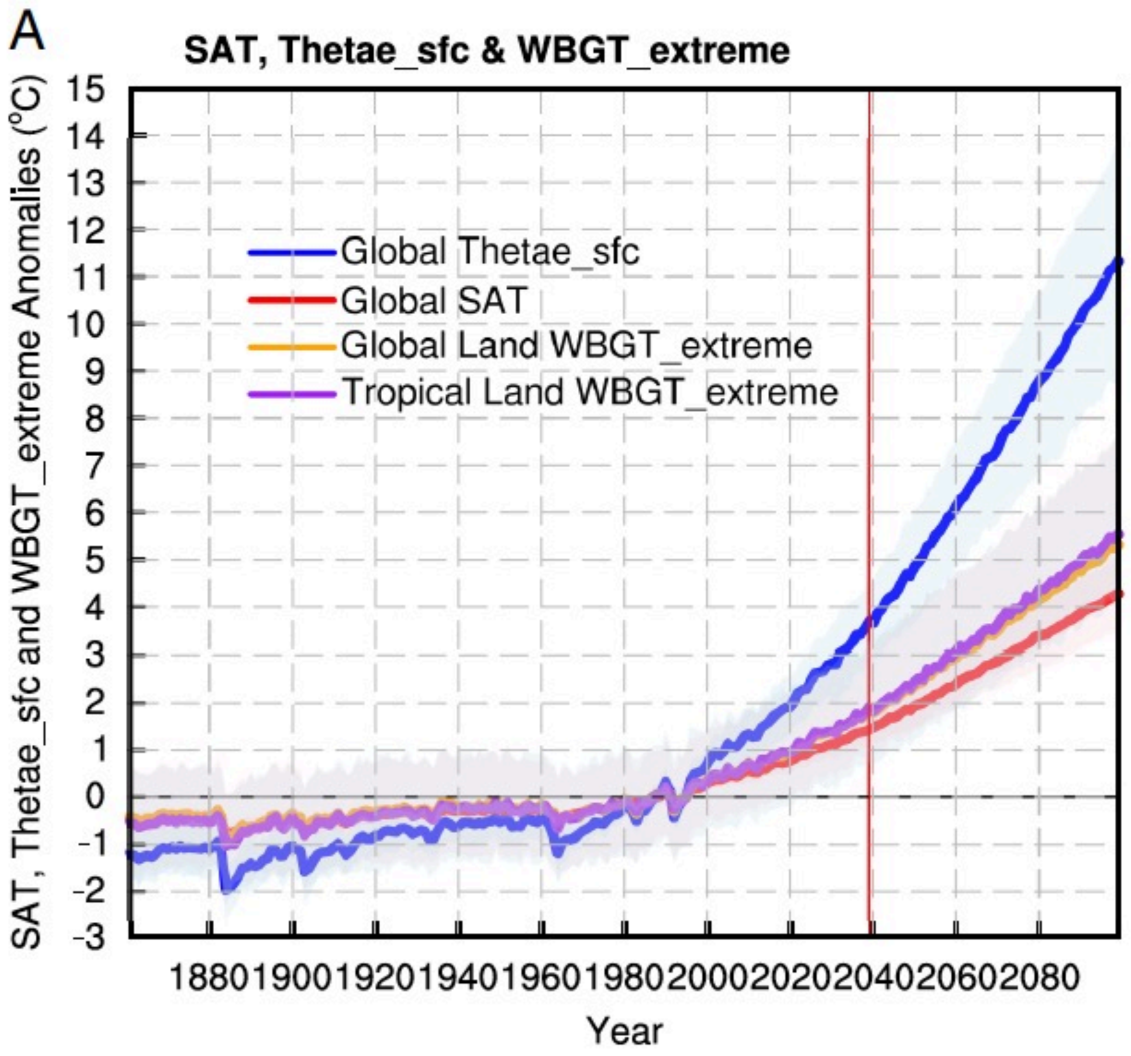


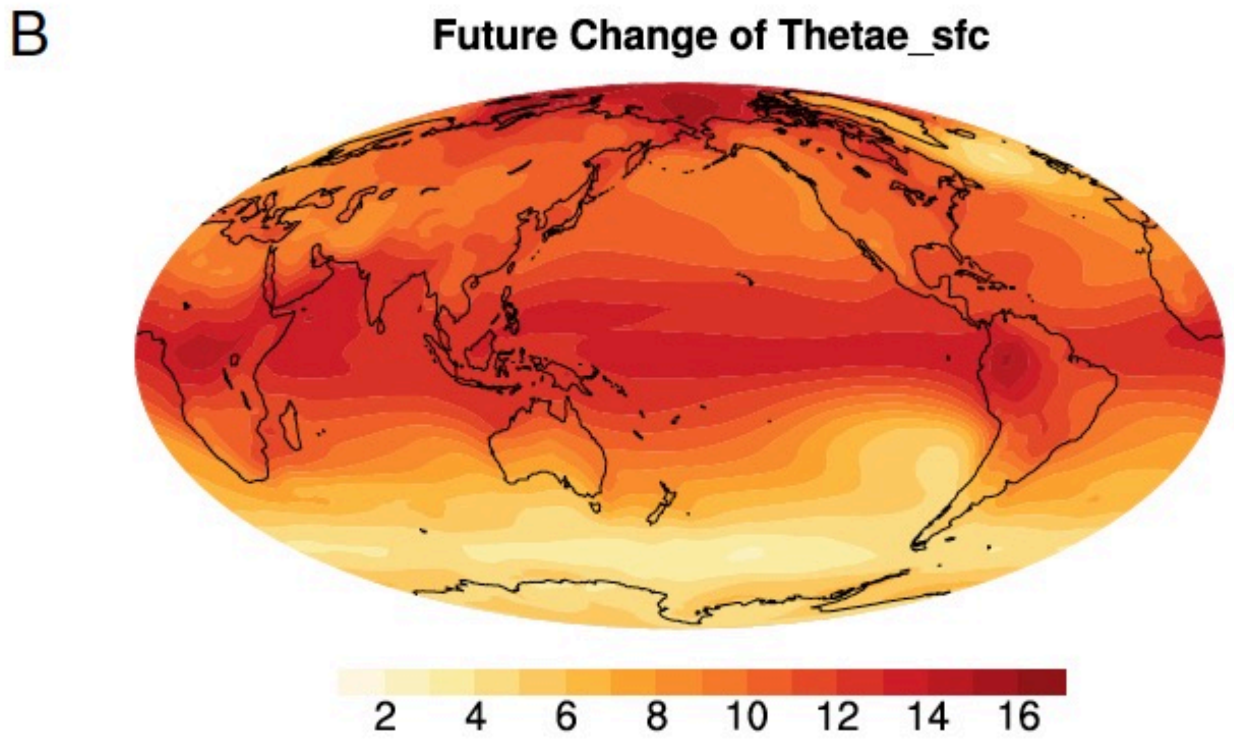
(Song et al. 2022 PNAS)

Why extreme weather events are expected to increase with global warming?

Much larger increase in thetae_sfc than SAT

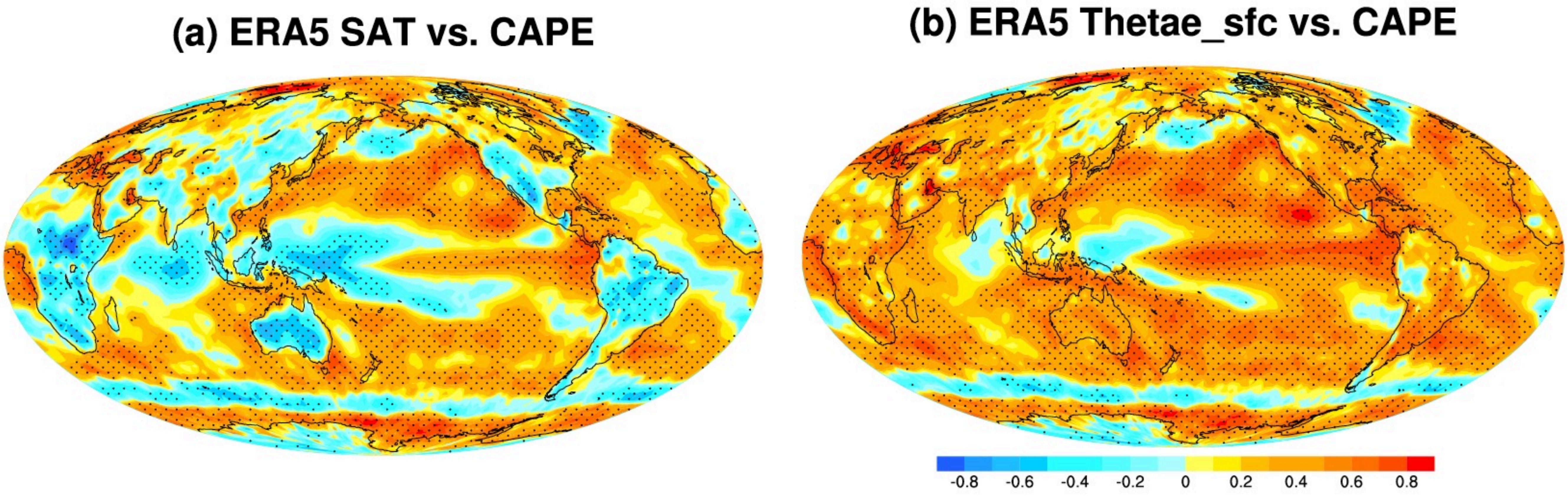
Larger warming in the tropics (more humidity) and Arctic (polar amplification) than mid-latitude





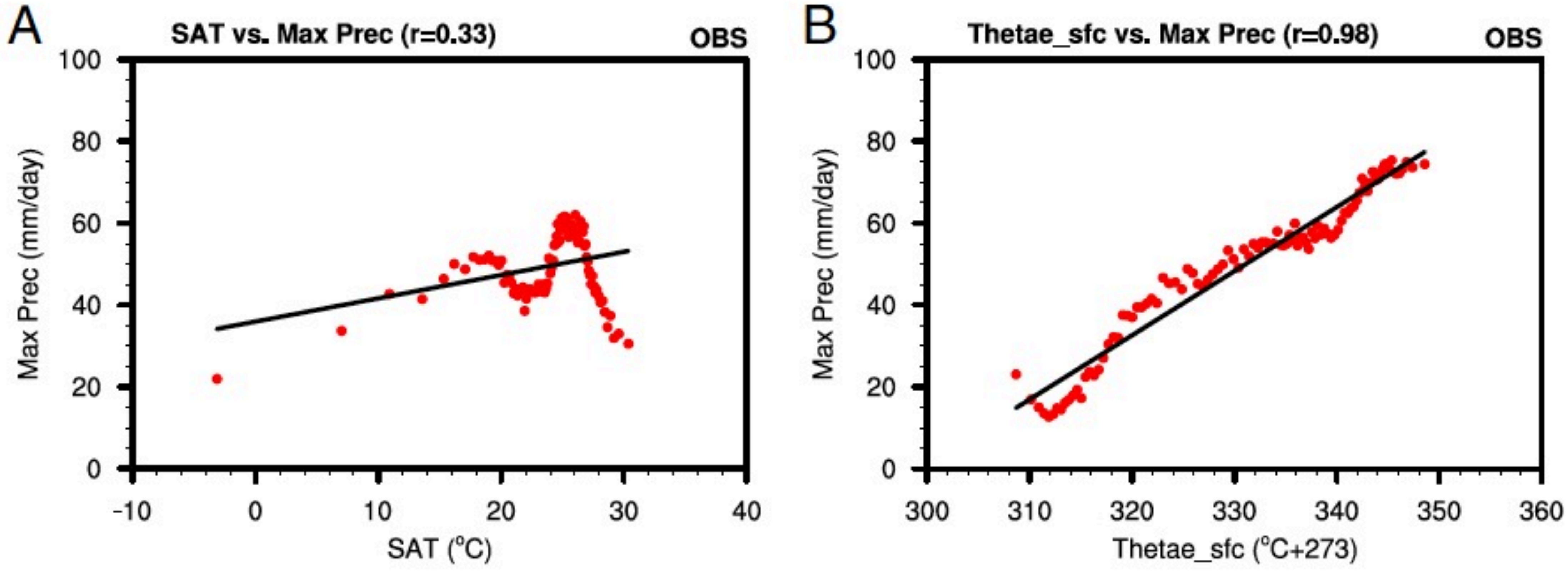
Why extreme weather events are expected to increase with global warming?

Convective available potential energy (CAPE) correlates more strongly with thetae_sfc than SAT, particularly over land



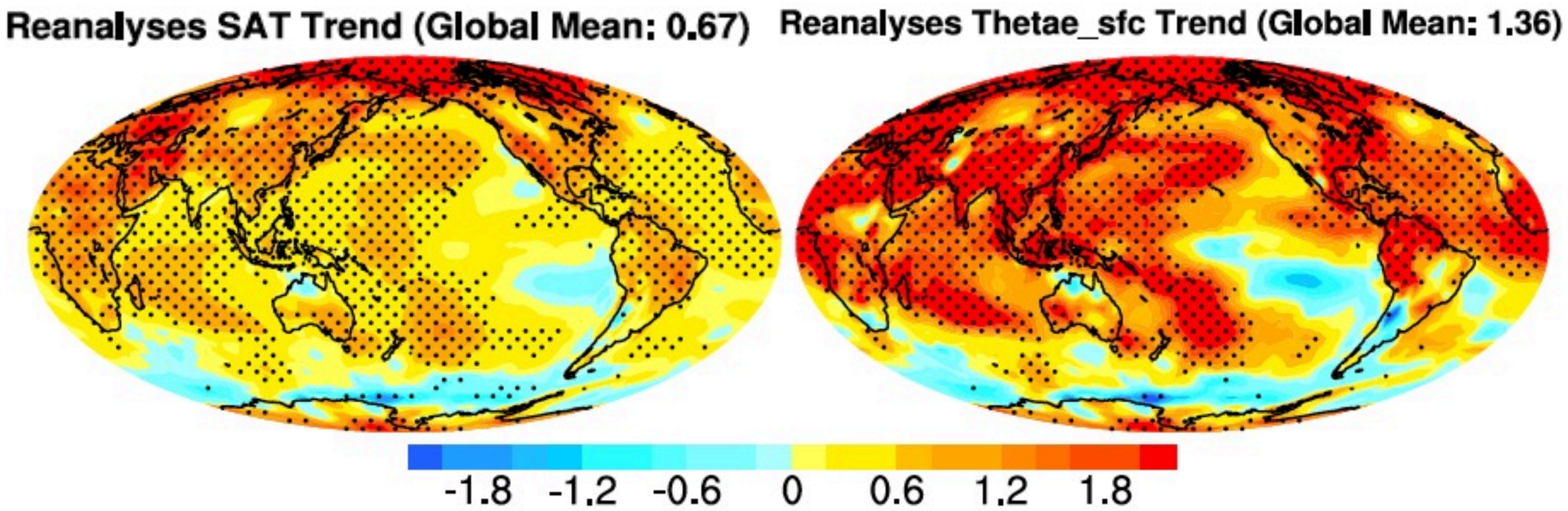
Why extreme weather events are expected to increase with global warming?

Annual maximum precipitation correlates more strongly with thetae_sfc than SAT

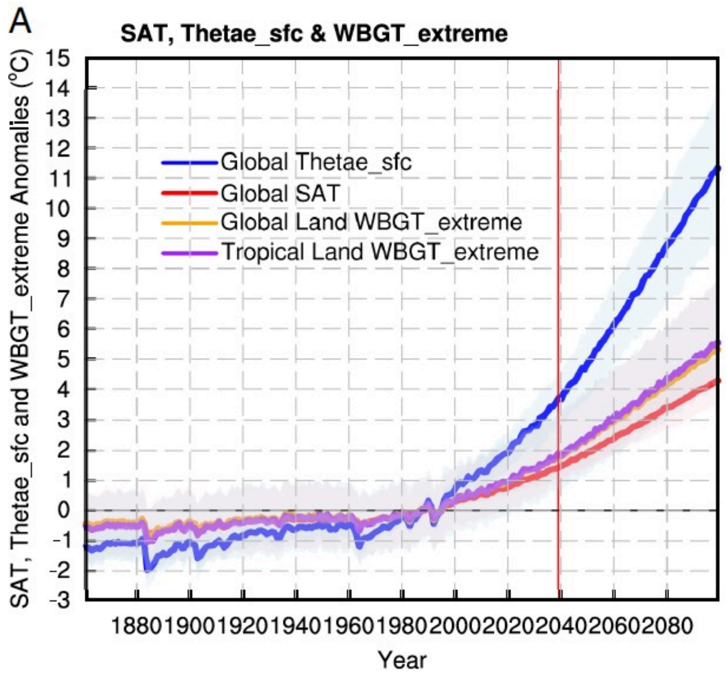


Much faster rate of increase in weather extremes than SAT warming rate!

Observed trends between 1980-2019



Global mean time evolution



- Warming rate measured by thetae_sfc is much higher than warming rate measured by SAT in both the past and future
- Weather extremes more strongly correlated with thetae_sfc
- Much faster rate of increase in weather extremes than quasi-linear SAT warming rate
- Setting warming targets based on thetae_sfc to limit changes in weather extremes has important policy implications

Outline

- Global warming increases extreme weather events
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- **Regional climate change in western U.S. – California as an example**
  - **Understanding the robust and non-robust changes projected by models**
- Strategies and progress in DOE Energy Exascale Earth System Model (E3SM)
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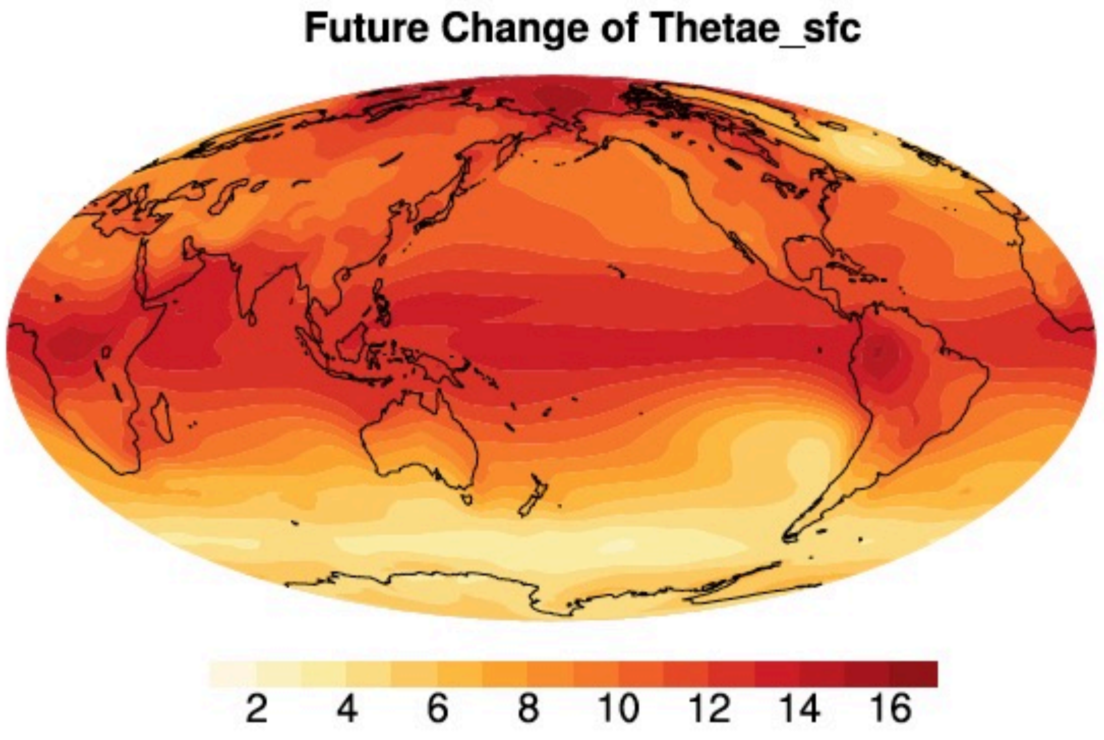
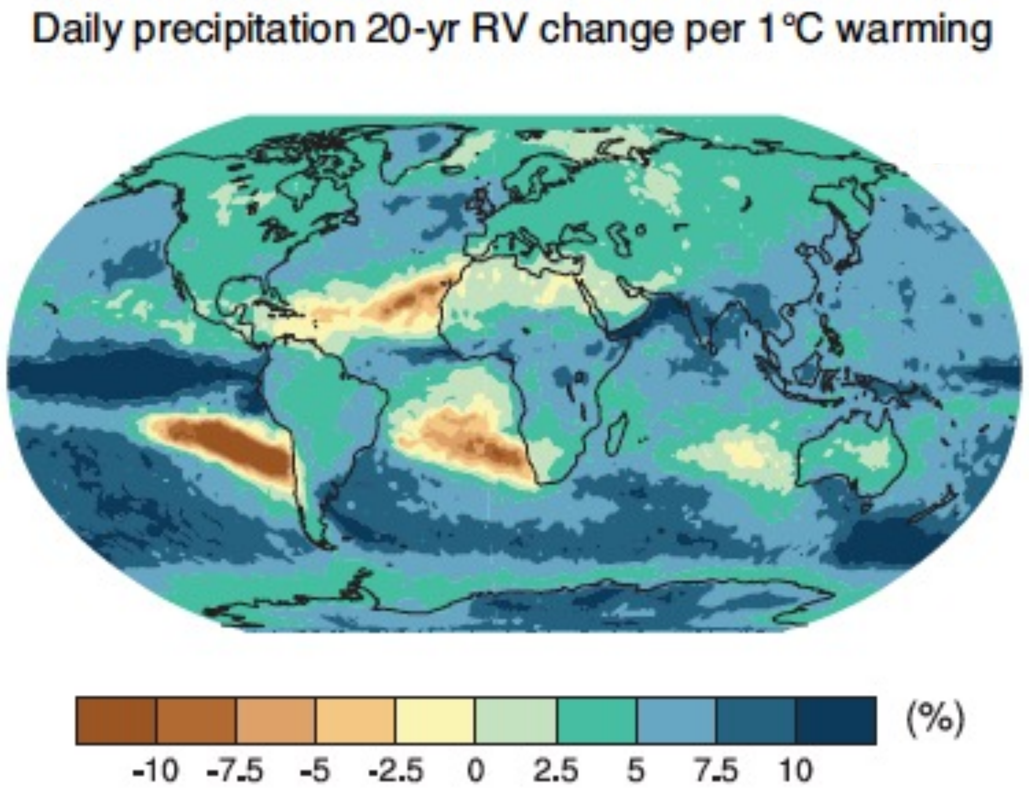
Regional differences in extreme precipitation changes are significant

- Despite relatively uniform increases in thetae_sfc, changes in extreme precipitation have large spatial heterogeneity – atmospheric circulation plays an important role

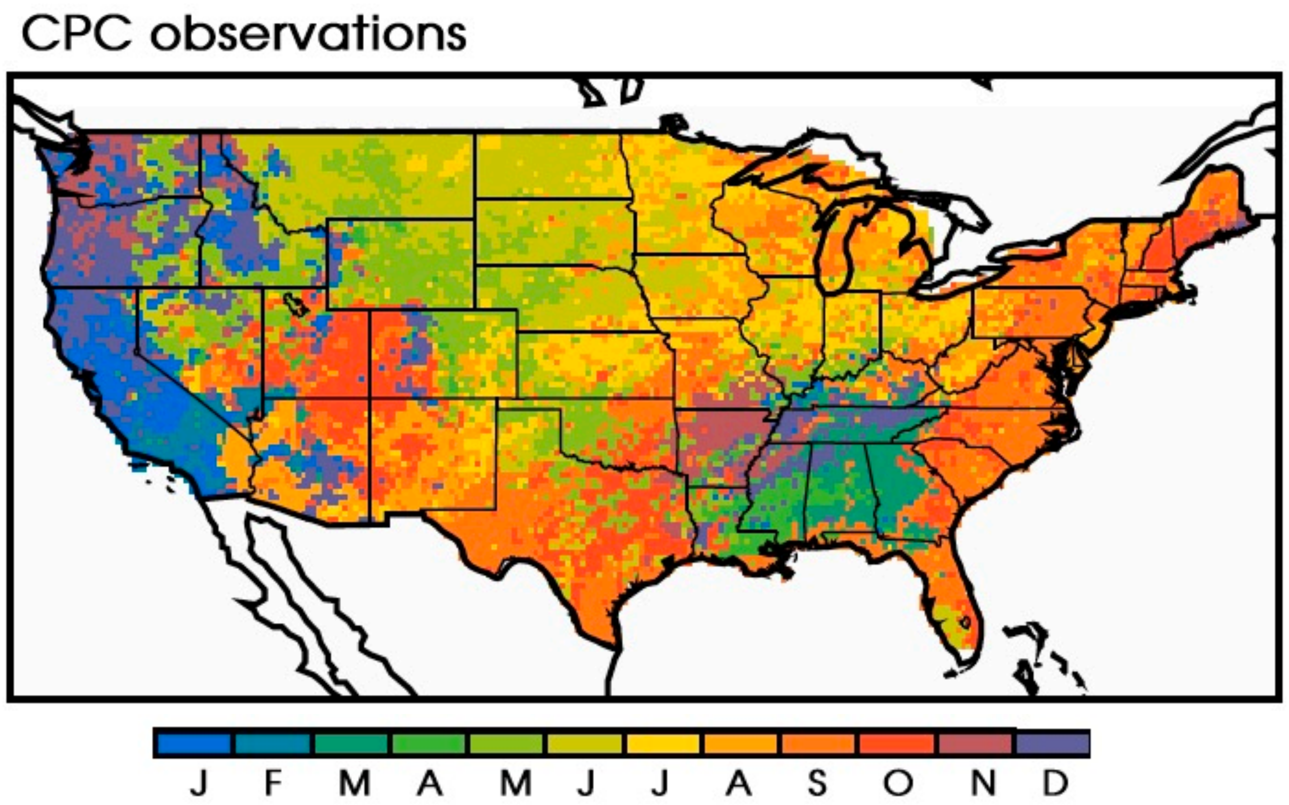




(IPCC AR5 WGI report)

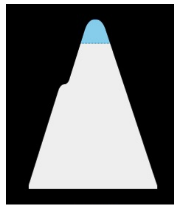
Seasonality is a key aspect in regional climate change

Timing of maximum monthly precipitation



(van der Wiel et al. 2016 J. Clim.)


Nov - Mar

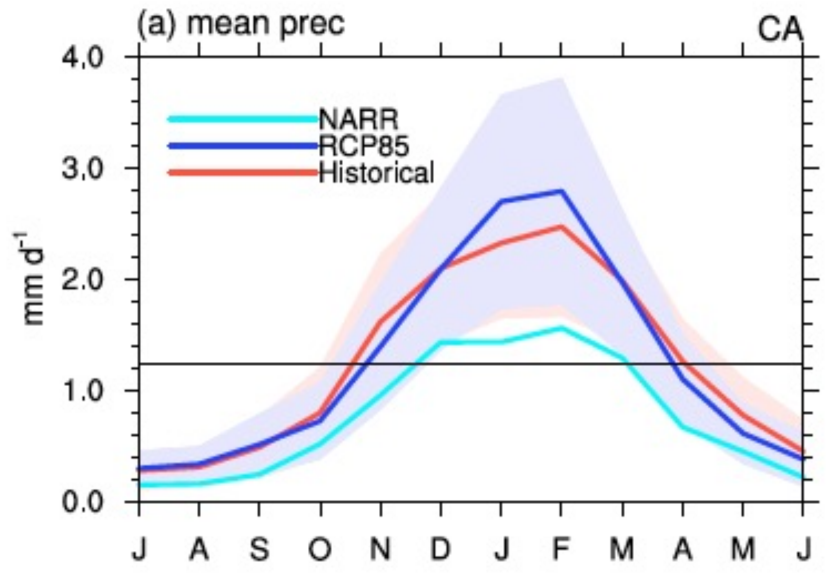

Feb - Apr

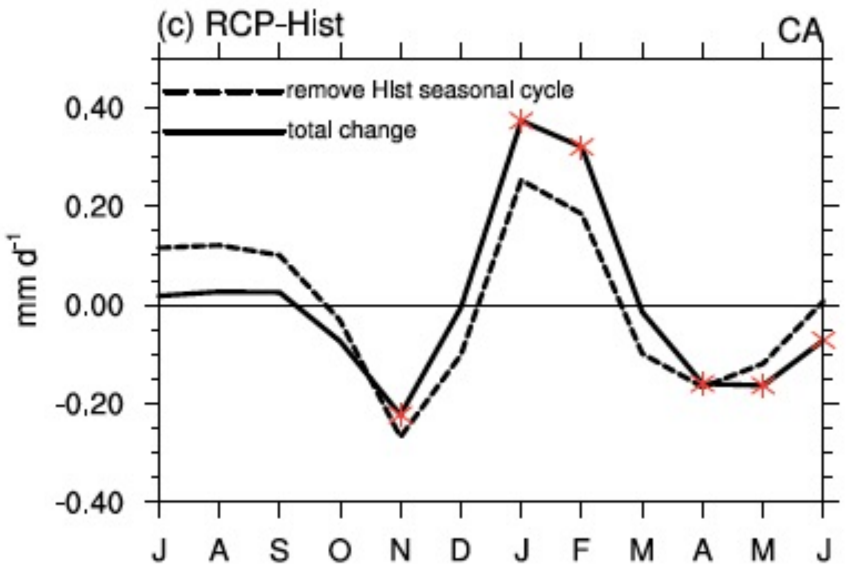

Apr - Jun

 
July - Oct

Robust sharpening of CA precipitation seasonal cycle

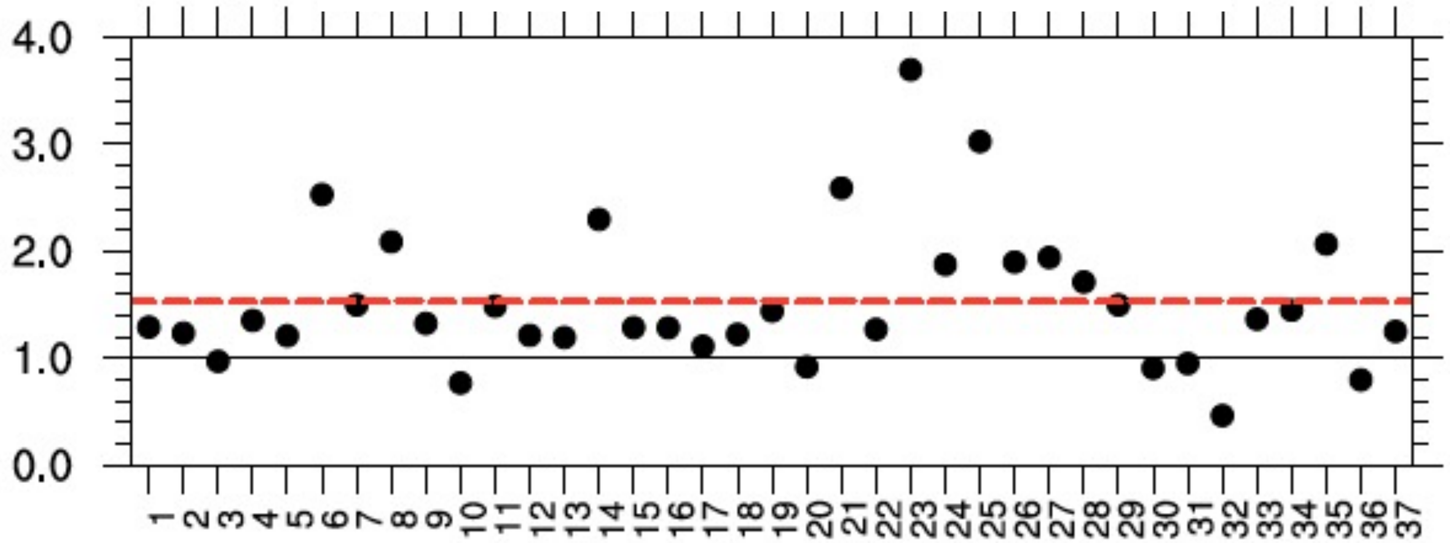
A stronger but narrower wet season is projected in the future under global warming





Sharpening wet season index: $\frac{\text{Future}(\,[\text{DJF} - (\text{MA} + \text{ON})/2]\,)}{\text{Hist}(\,[\text{DJF} - (\text{MA} + \text{ON})/2]\,)}$

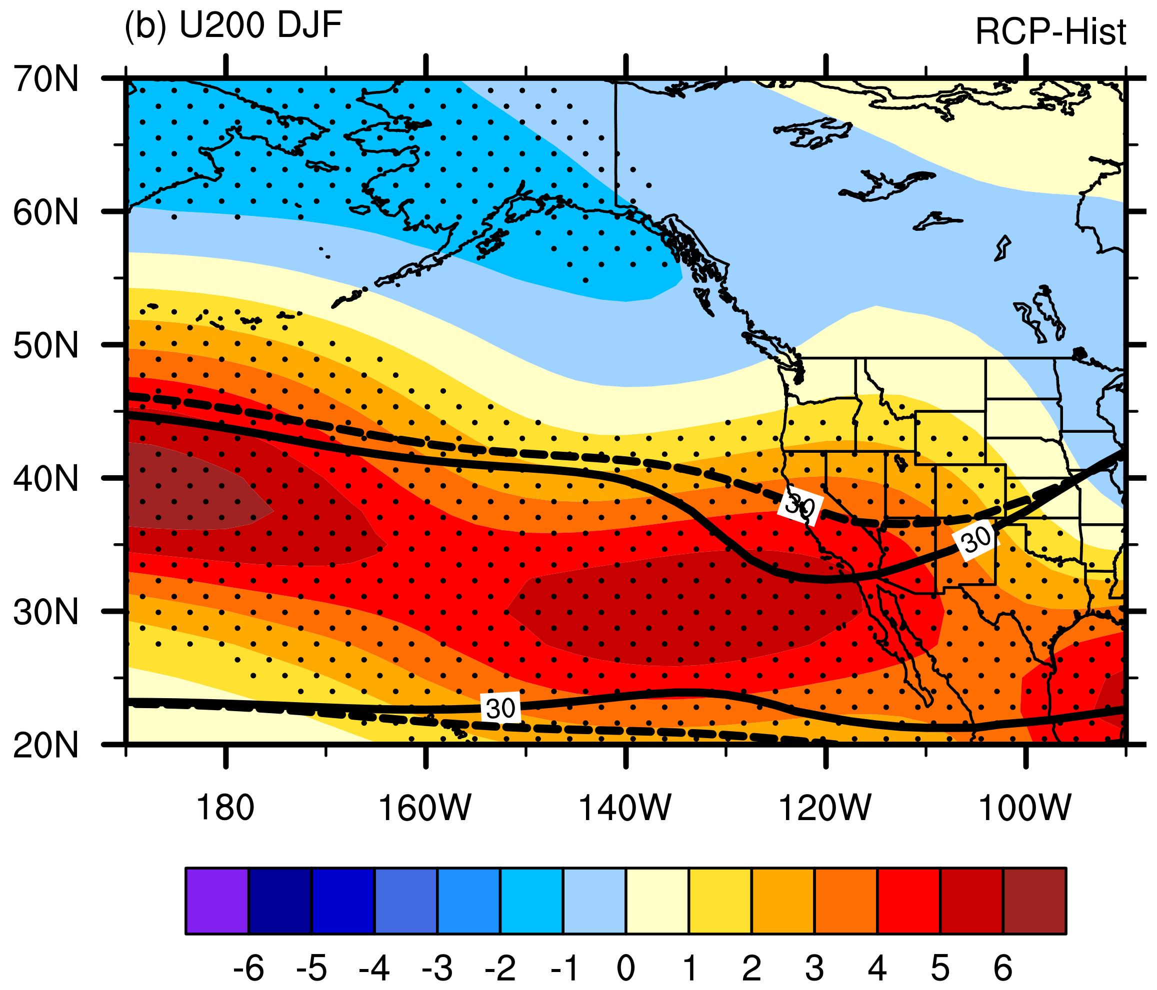
Sharpening of precipitation seasonal cycle



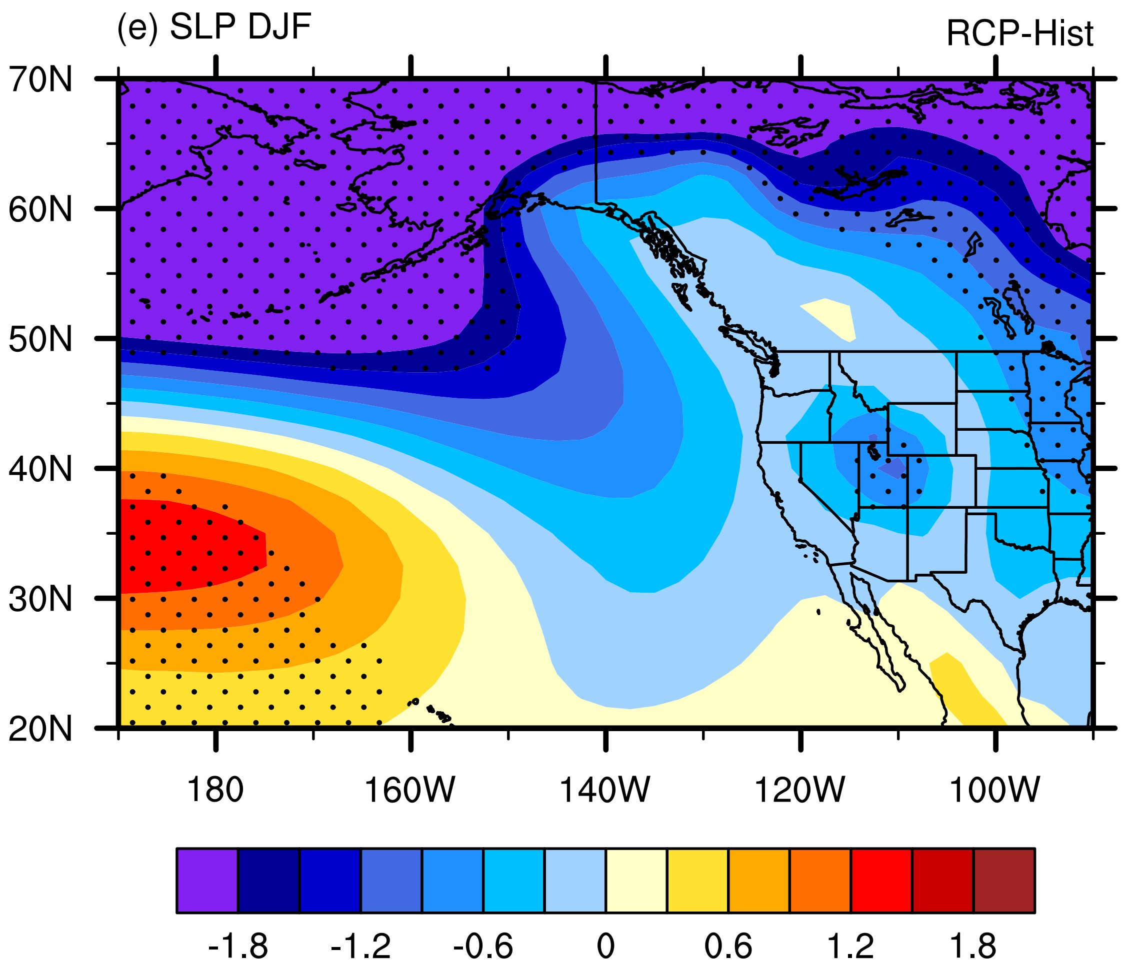
(Dong et al., 2019 JCLIM)

Mechanisms for the sharpening: winter changes driven by circulation changes

Eastward extension of westerly jet – steer storm tracks toward CA



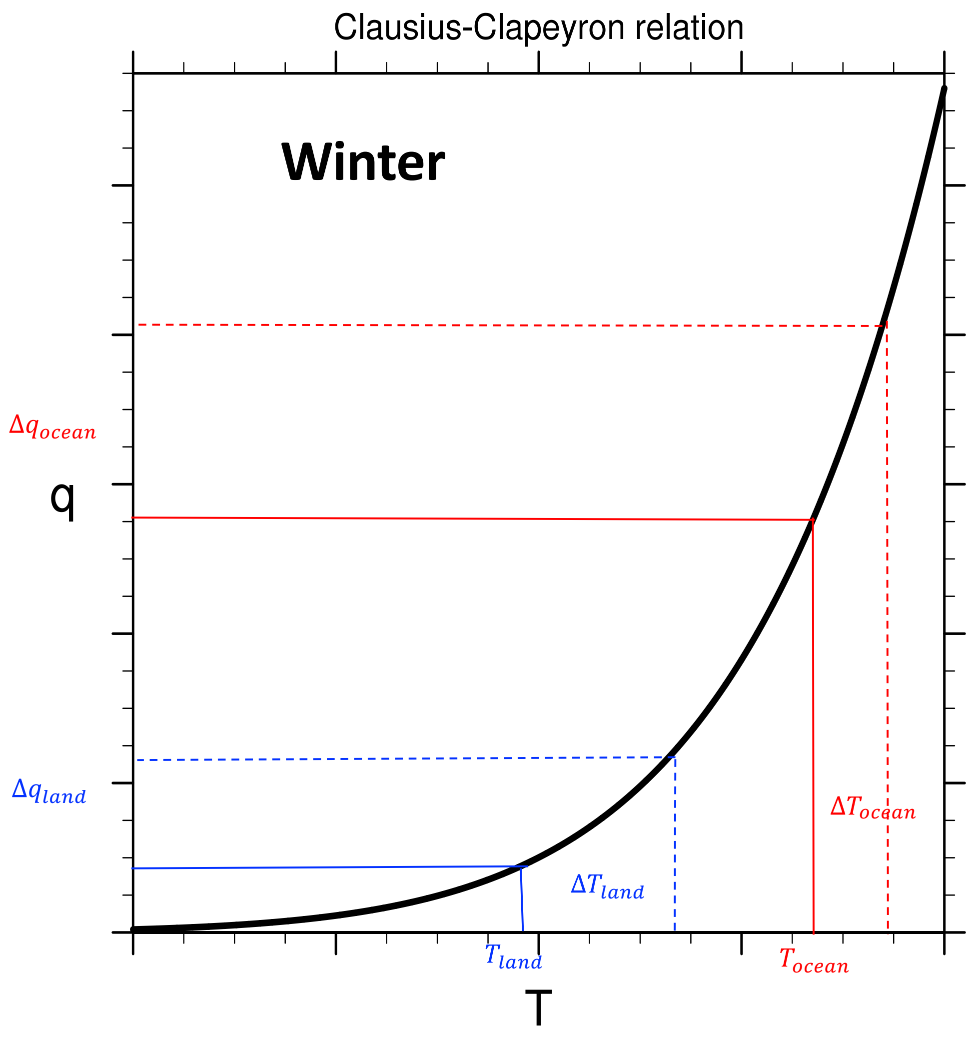
Deepening of Aleutian Low – cyclonic circulation increases moisture advection to CA

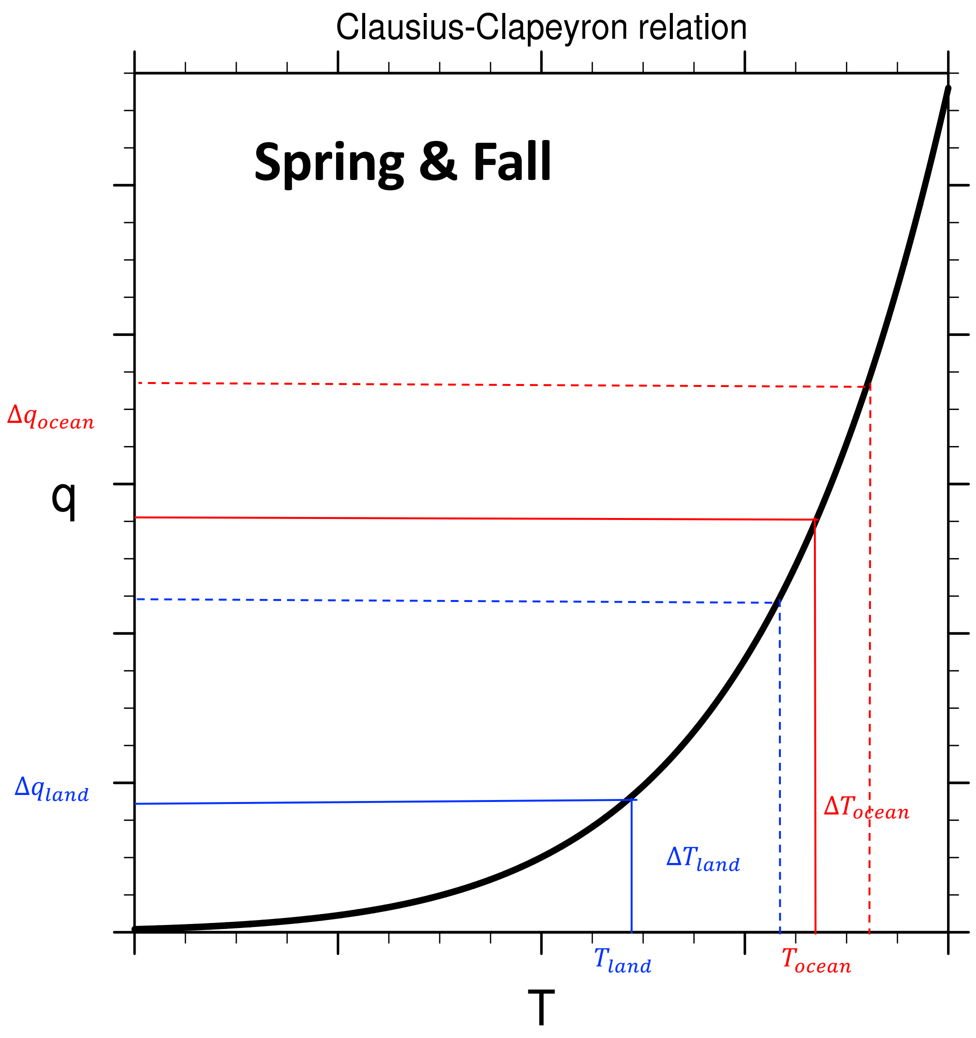


Mechanisms for the sharpening: winter vs. spring/fall contrast driven by land-sea warming contrast

Prevailing westerlies advect moisture from ocean to land: depends on land-ocean warming contrast and nonlinear CC relation

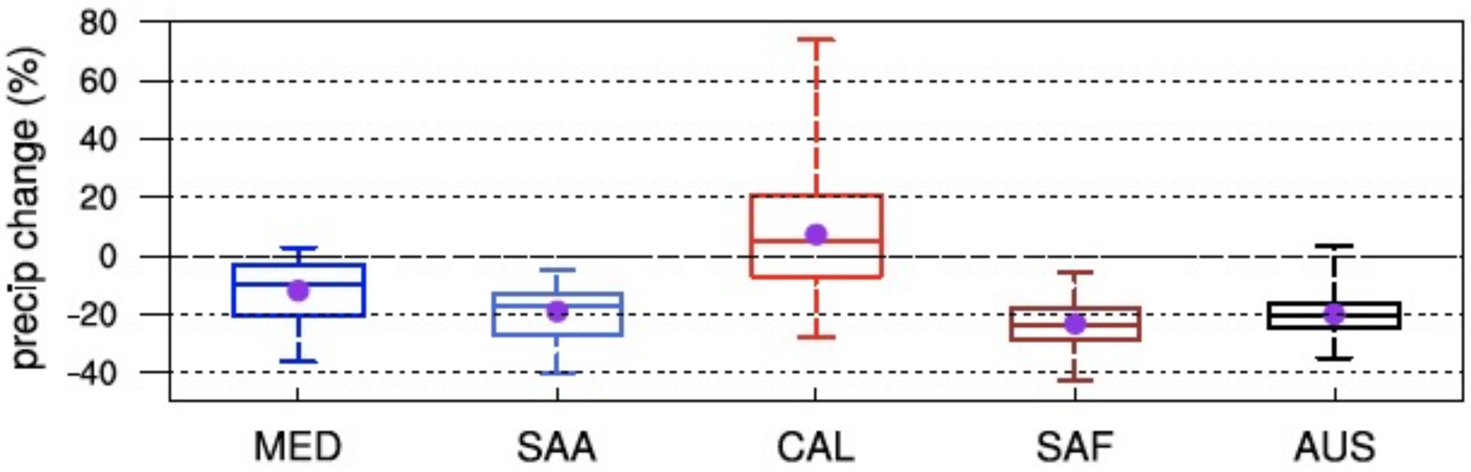
$$T_{land} < T_{ocean}, \Delta T_{land} > \Delta T_{ocean} \longrightarrow \Delta q_{land}\ vs\ \Delta q_{ocean}?$$





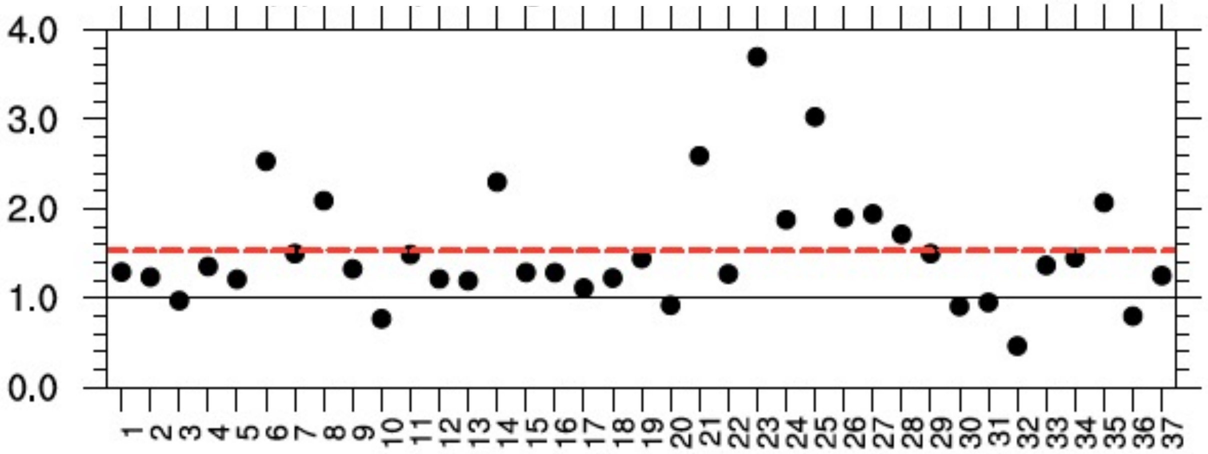
CA winter precipitation changes are highly uncertain

Winter Precipitation amount change



(Polade et al., 2017 Sci. Rep.)

Sharpening of precipitation seasonal cycle



(Dong et al., 2019 JCLIM)

Including large ensemble simulations in the analysis

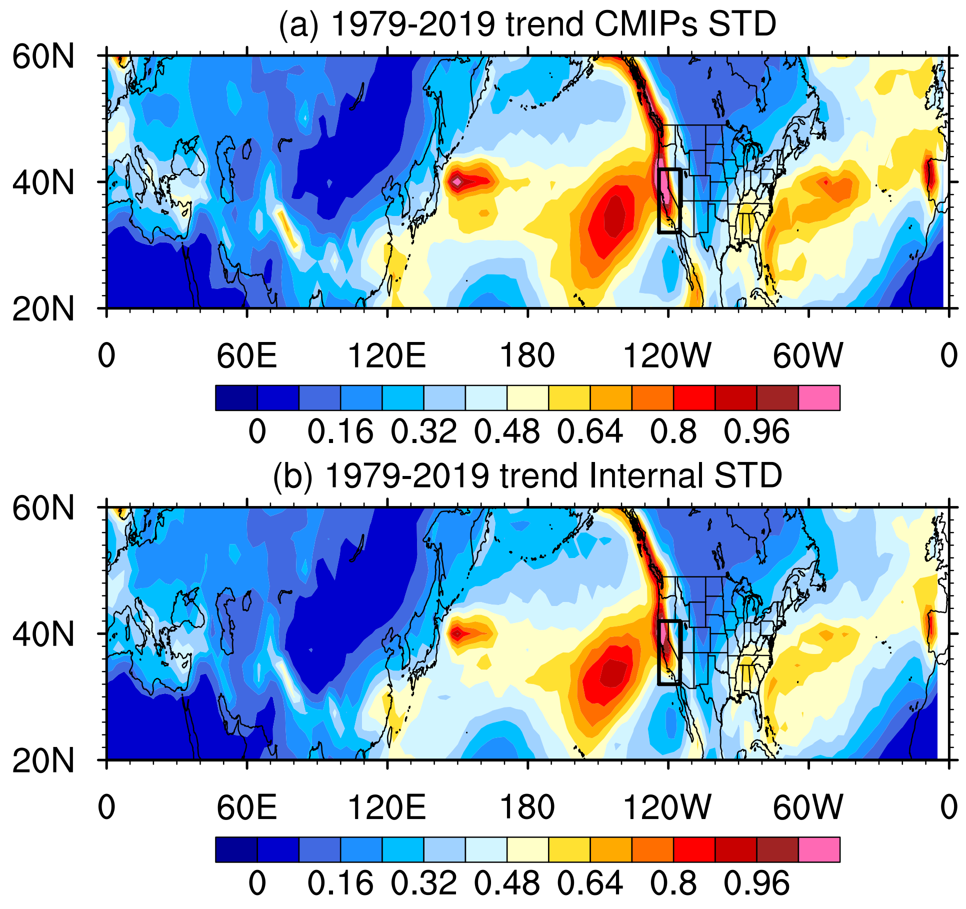
- 128 simulations from the multi-model CMIP5 and CMIP6 ensembles (some models include small ensembles of 3 members)
- 190 simulations from three large ensemble simulations (CESM1 (40), CanESM2 (50), MPI-ESM (100)
- A total of 318 simulations from CMIP (spread = model differences + internal variability) and multiple perturbed initial condition large ensemble simulations (spread = internal variability)

(Dong et al. 2021 Nature Commun.)

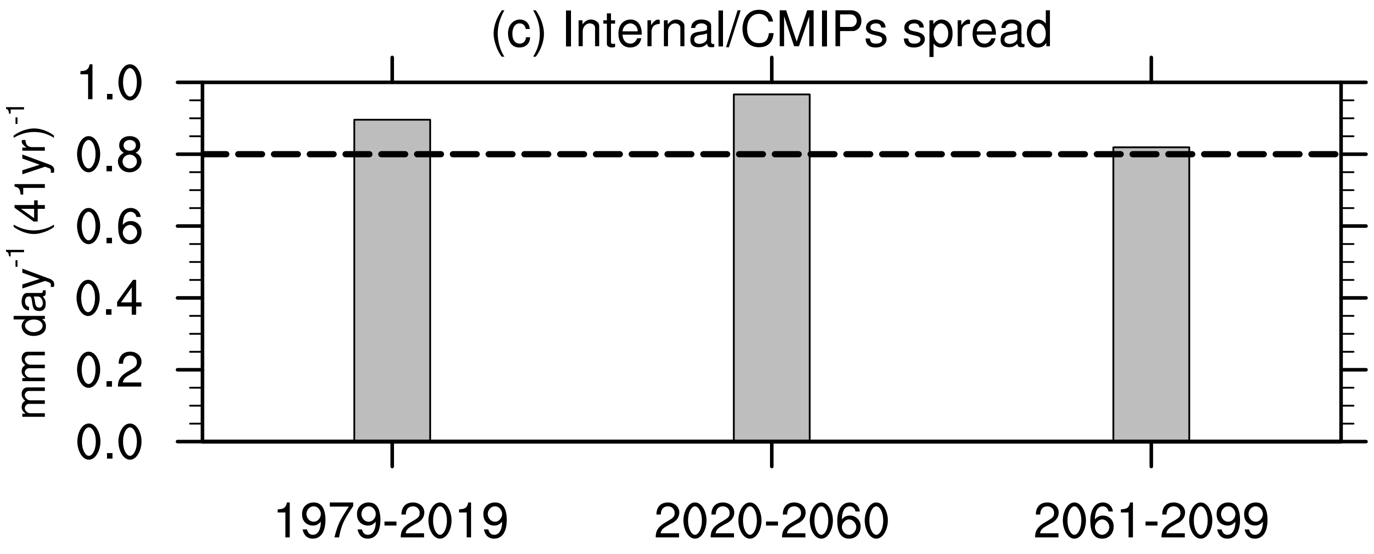
CA precipitation trend during 1979-2019

- During 1979-2019, observed precipitation in CA has decreased by 28%
- Large standard deviation (STD) in model simulated CA precipitation trends for the same period

Large uncertainty in winter precipitation over CA and the North Pacific storm track region

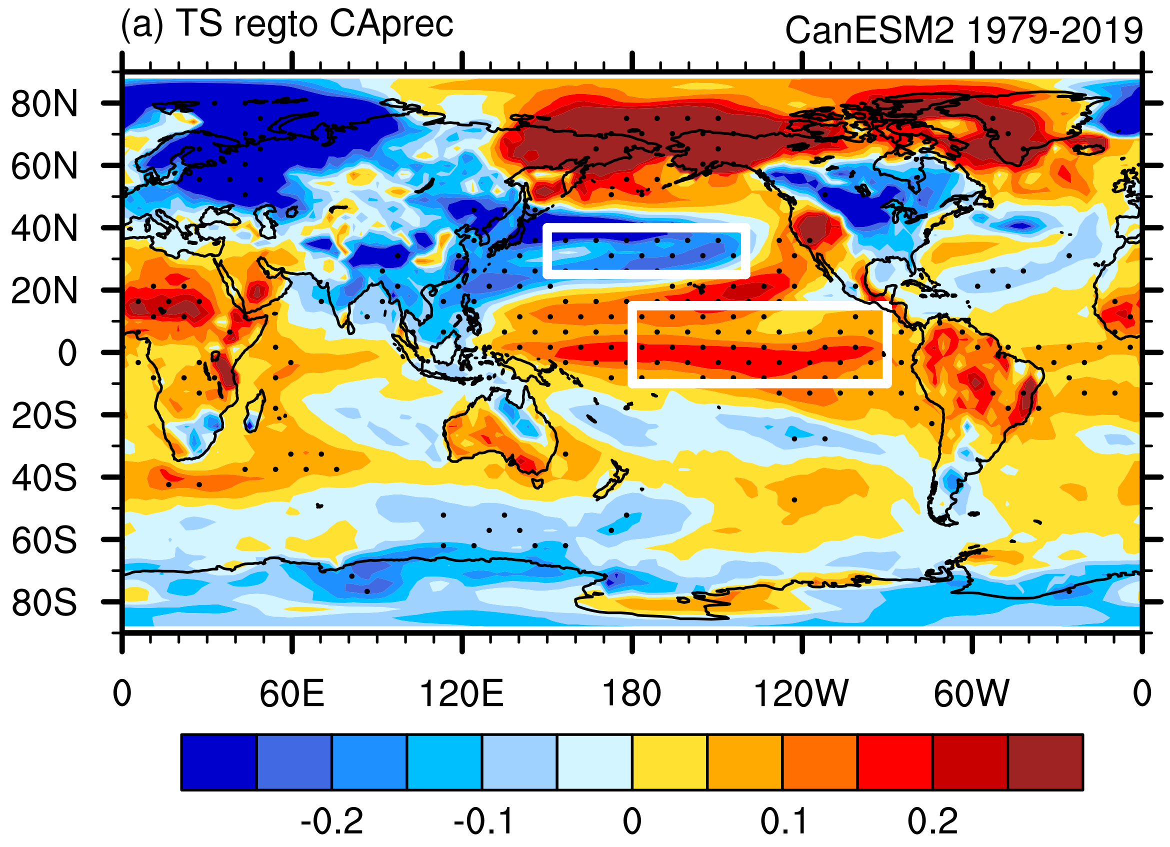


Internal variability contributes to > 80% of the total uncertainty in CA precipitation trend during 1979-2019

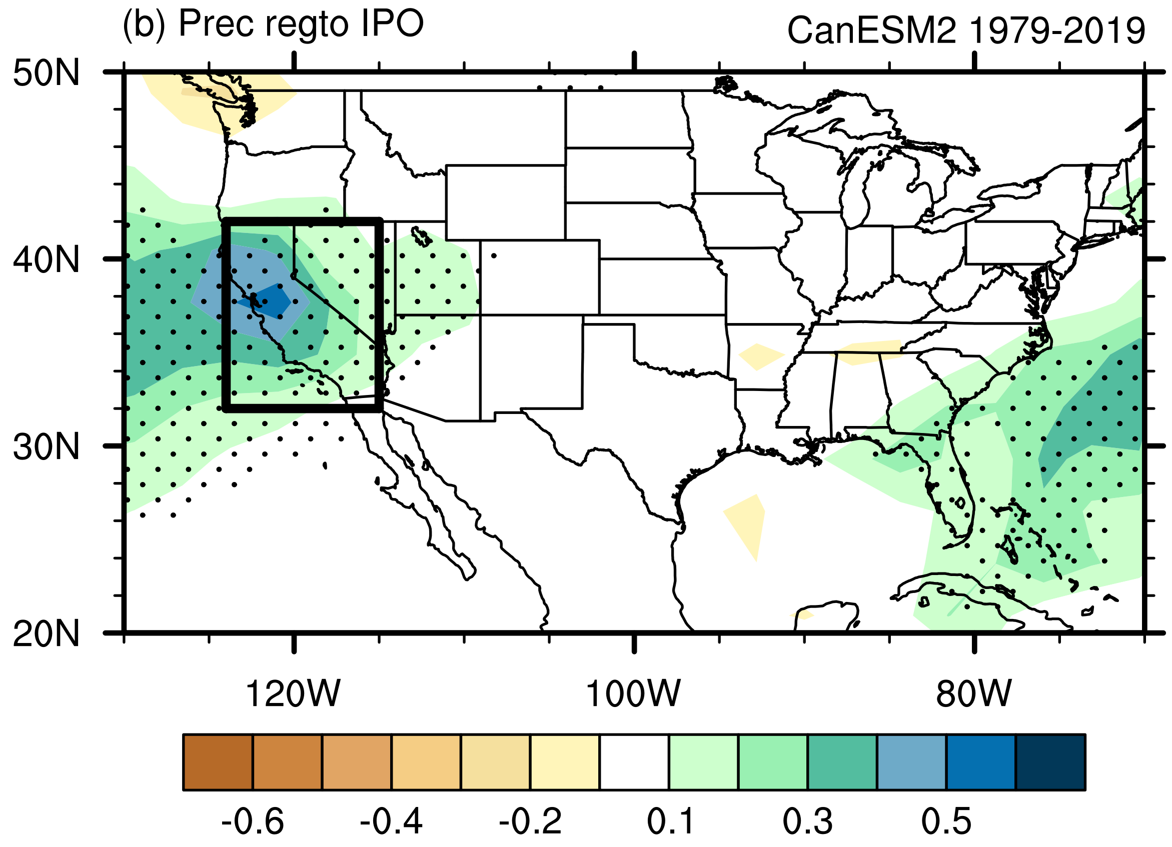


Strong connection between Interdecadal Pacific Oscillation (IPO) trend and CA precipitation trend

Inter-member correlation between CA precipitation trend and surface temperature trend shows the signature of IPO in the Pacific Ocean

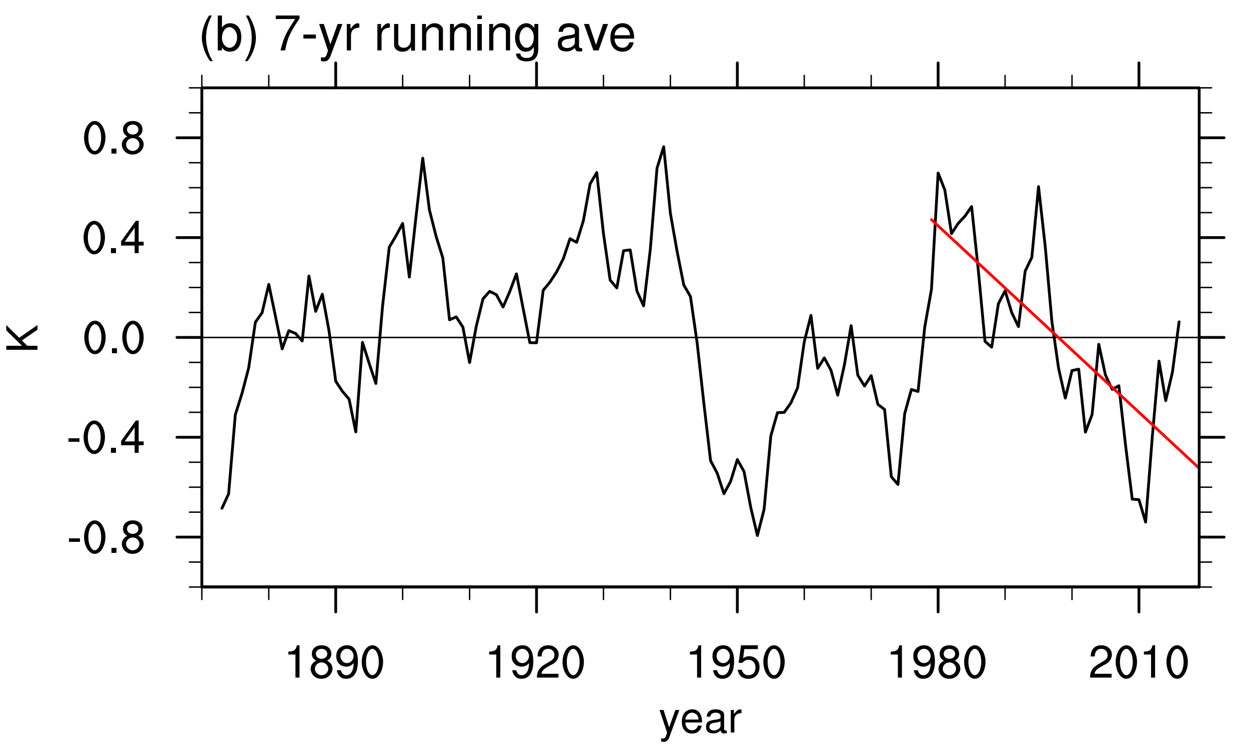


Strong correlation between IPO trend and CA precipitation trend

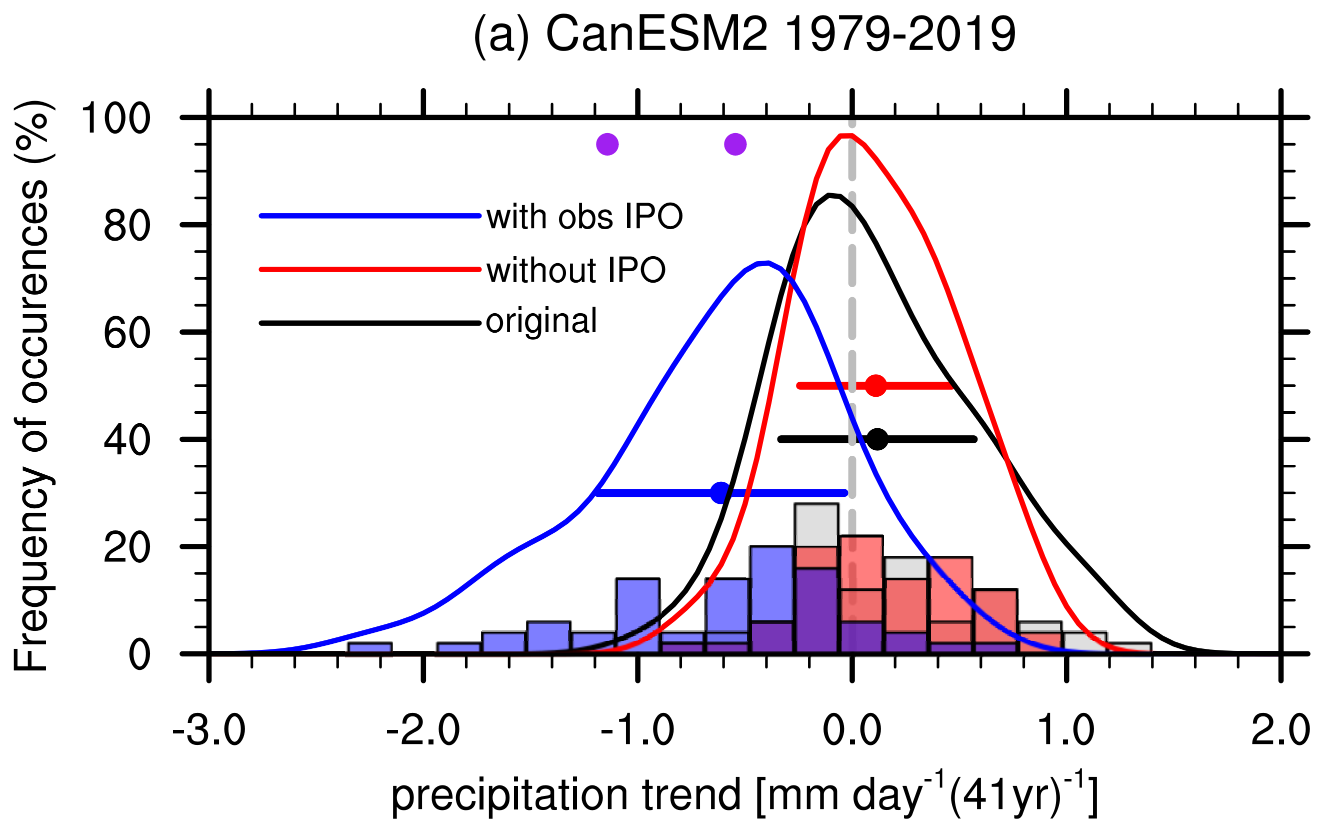


The CA drying trend in 1979-2019 is dictated by the positive-to-negative IPO phase transition

A negative trend in IPO during 1979-2019 in observation

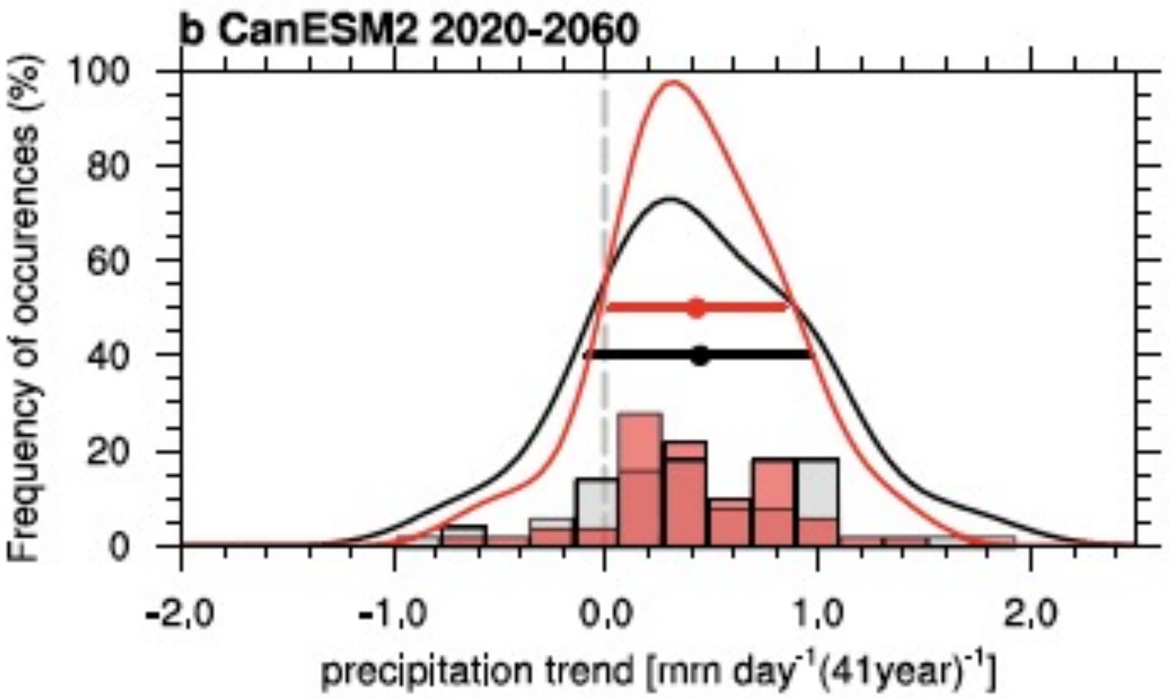


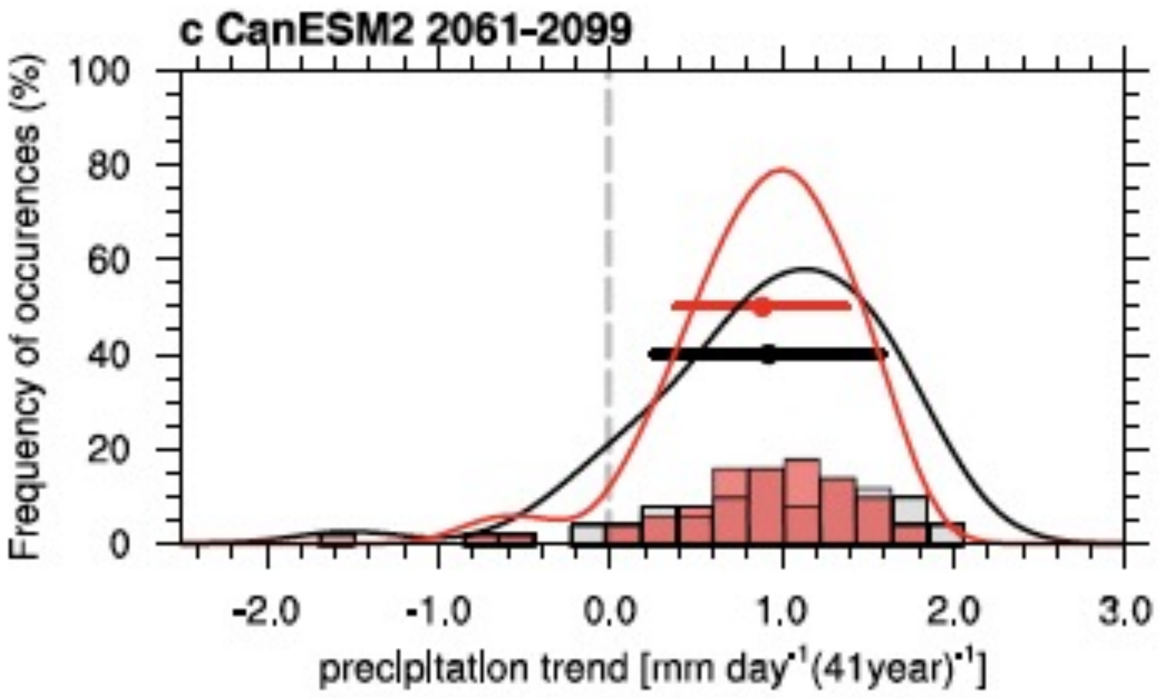
Accounting for the observed IPO trend shifts the PDF of precipitation trend from the large ensemble to within observational uncertainty



Large uncertainty remains in future projections due to internal variability

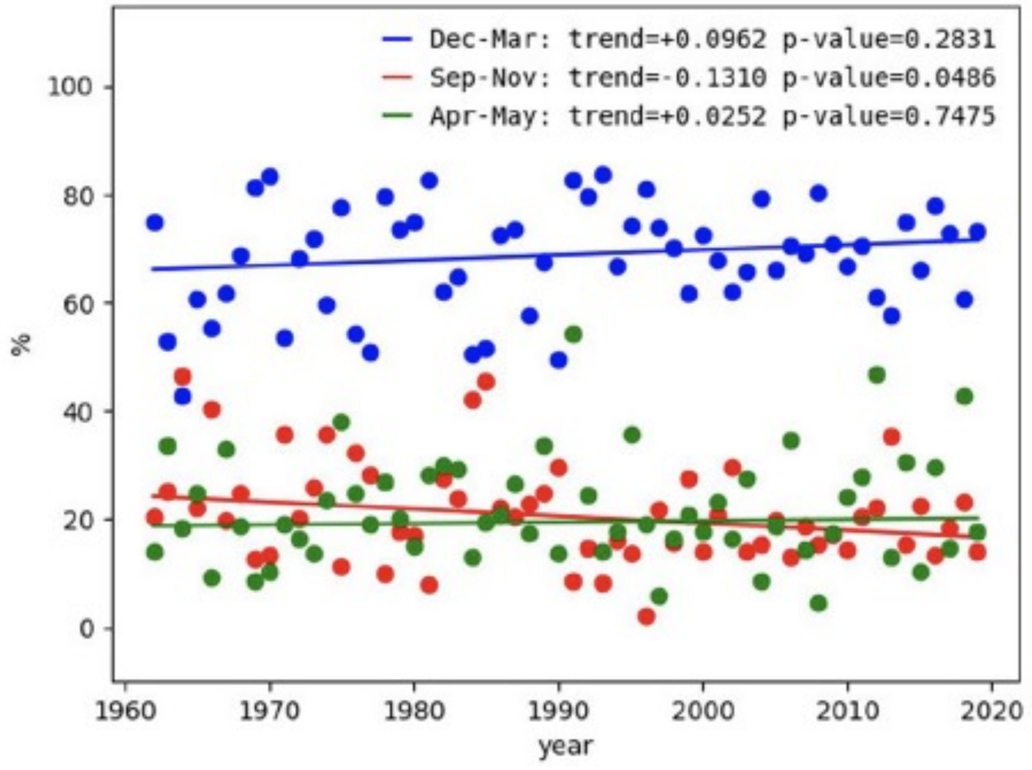
As greenhouse gases continue to increase, their impact on CA decadal trend increase, but uncertainty due to internal variability remains large





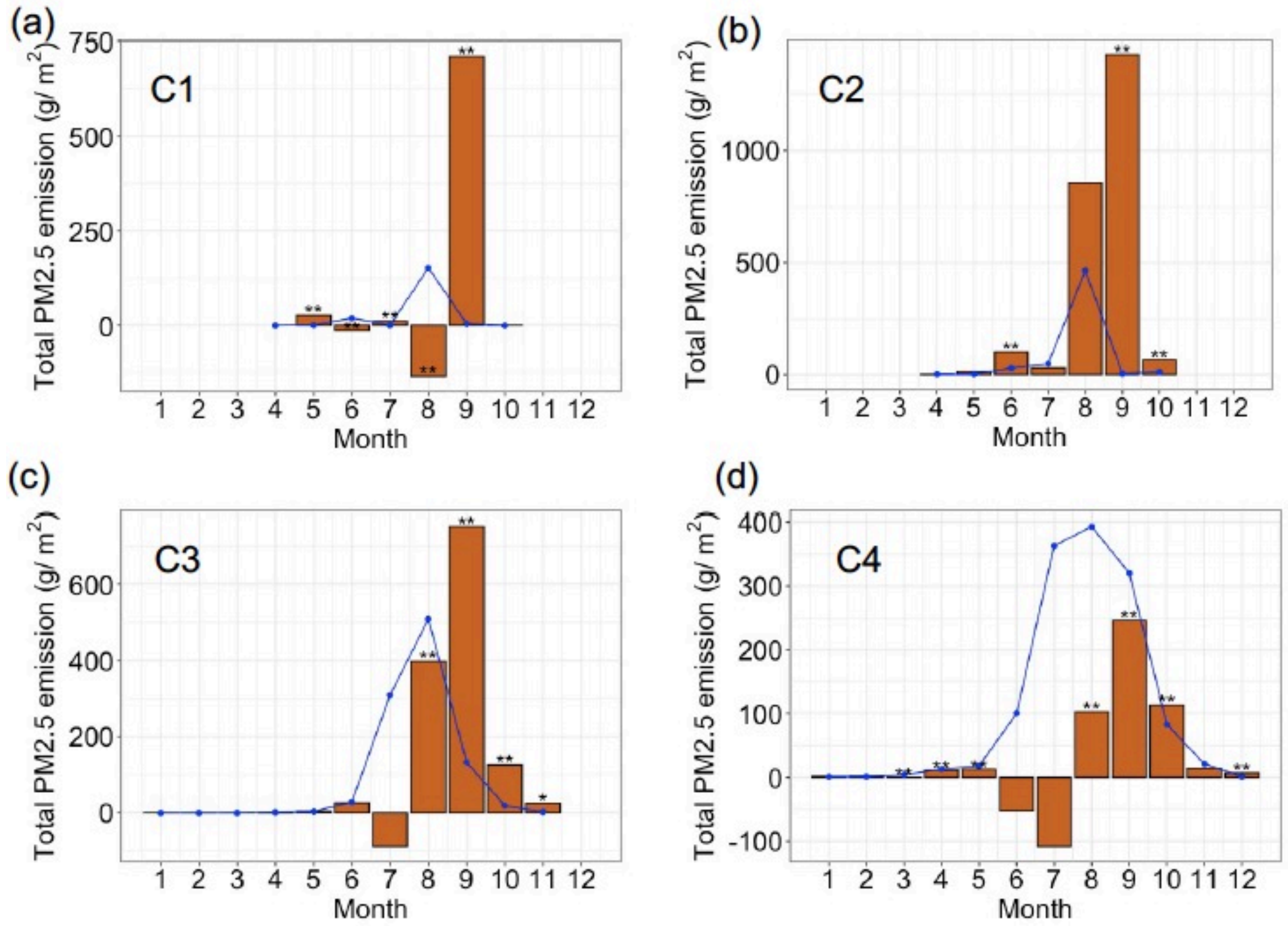
Implications of sharpening precipitation seasonal cycle to wildfires

Increasing/decreasing fraction of precipitation in DJFM/SON has been observed



(Luković et al., 2021 GRL)

Very large fire emissions increased significantly in September and October in 2010-2020 relative to 2000-2009, contributed by ~30-130% larger decreasing trends in fuel moisture in autumn than summer



(Wang et al., in review)

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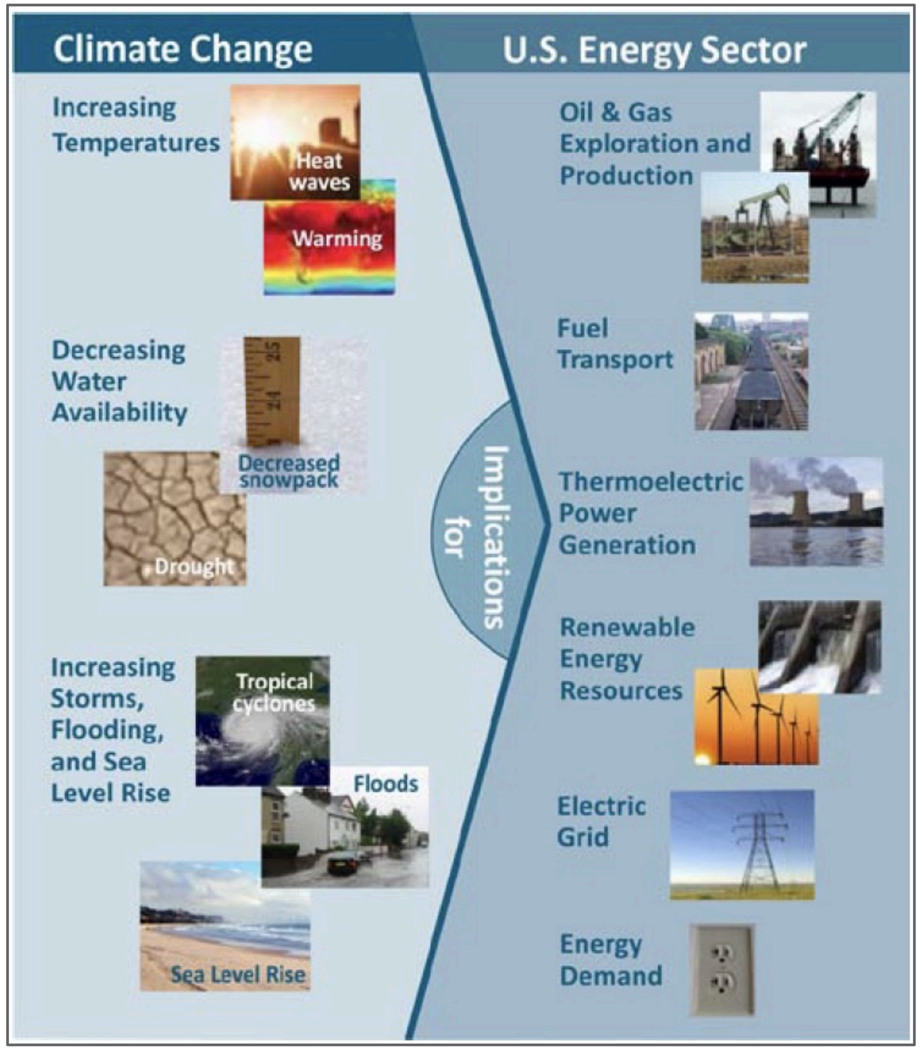
Energy Exascale Earth System Model (E3SM): Three overarching science drivers



(DOE report 2013)

- **Water cycle:** How does the hydrological cycle interact with the rest of the human-Earth system on local to global scales to determine water availability and water cycle extremes?
- **Biogeochemistry:** How does the biogeochemical cycle interact with other Earth system components to influence energy-sector decisions?
- **Cryosphere systems:** How do rapid changes in cryospheric systems evolve with the Earth system and contribute to sea level rise and increased coastal vulnerability?

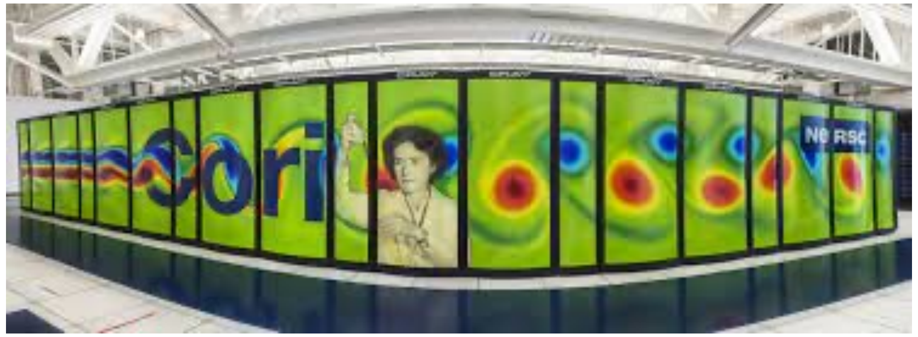
E3SM actionable science goals

- High-resolution modeling of extreme weather events in a changing climate
- Represent natural, managed and manmade systems and their interactions to project future outcomes
- Ensemble modeling to quantify uncertainty

Earth system science  Computational science

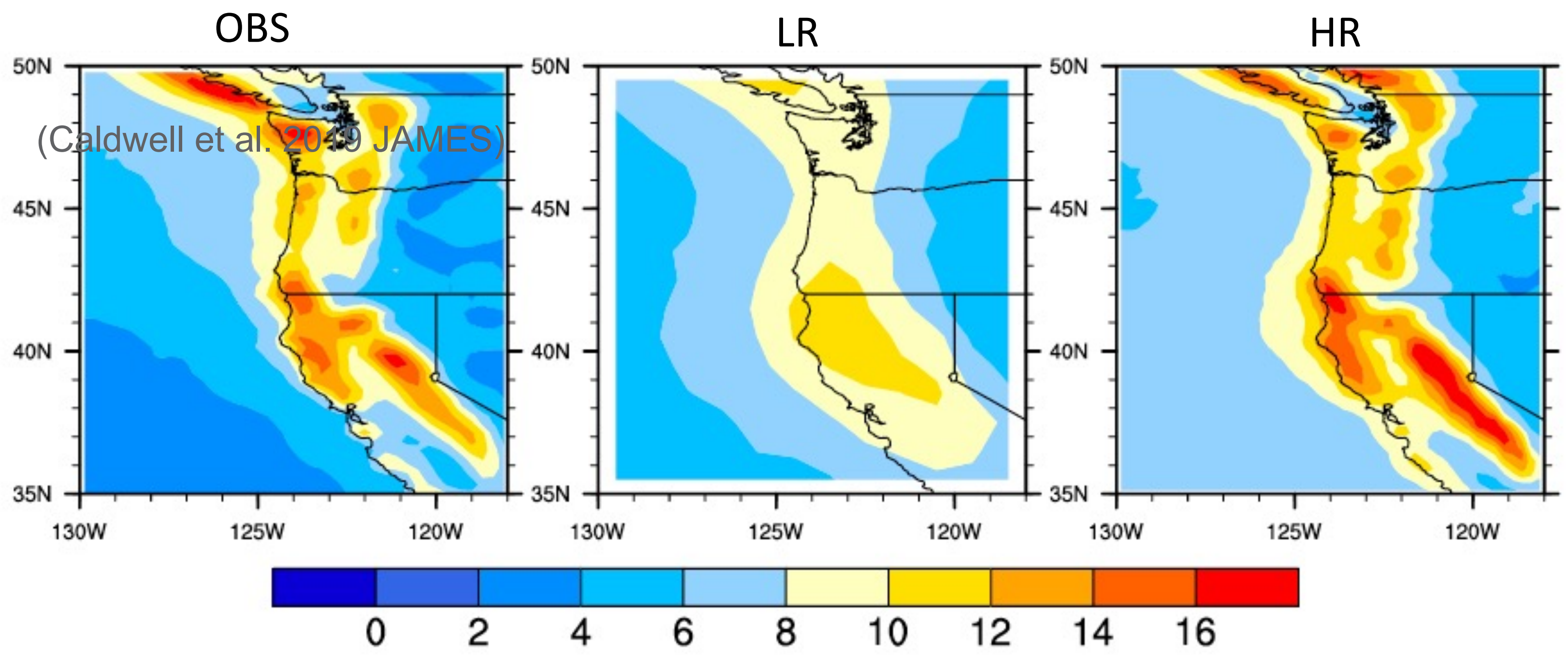
Modeling across scales on DOE computers

Model component	Low resolution (LR)	High resolution (HR)	Storm-resolving resolution	Regional refined meshes (RRM)
Atmosphere & Land	100 km	25 km	3 km	variable
Ocean & Ice	30-60 km	6-18 km	6-18 km	variable
River	50 km	12 km	12 km	variable



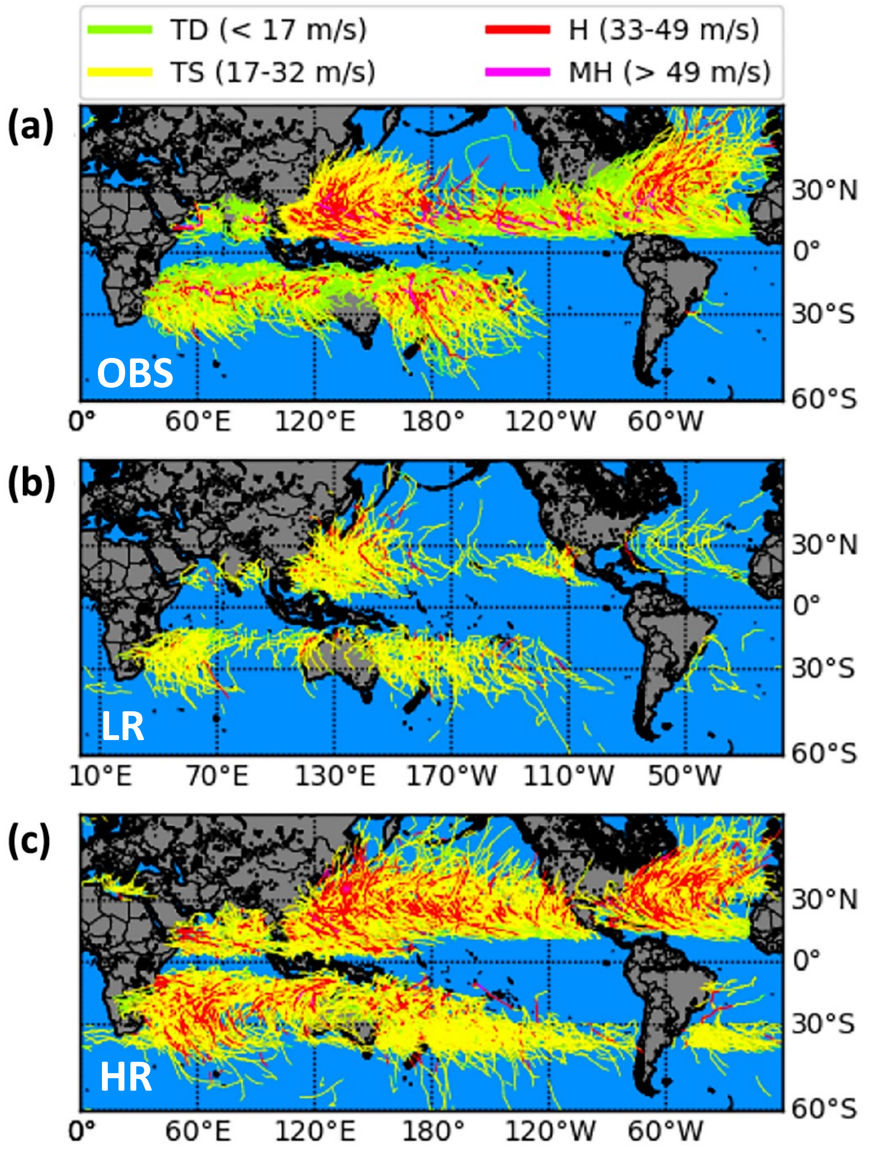
High resolution supports actionable science

HR improves precipitation over complex terrain



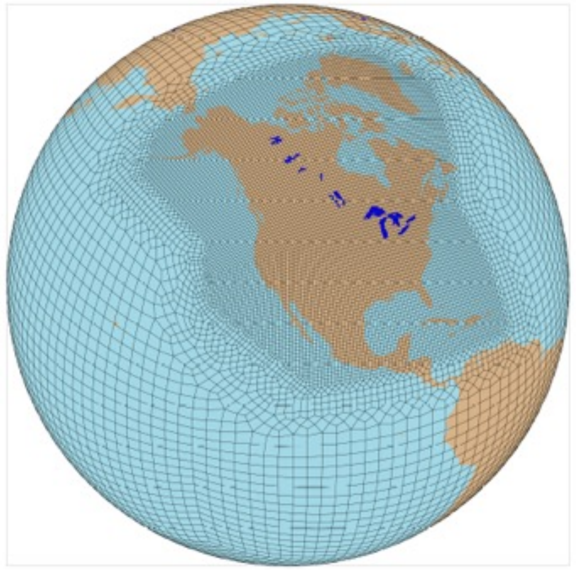
(Caldwell et al. 2019 JAMES)

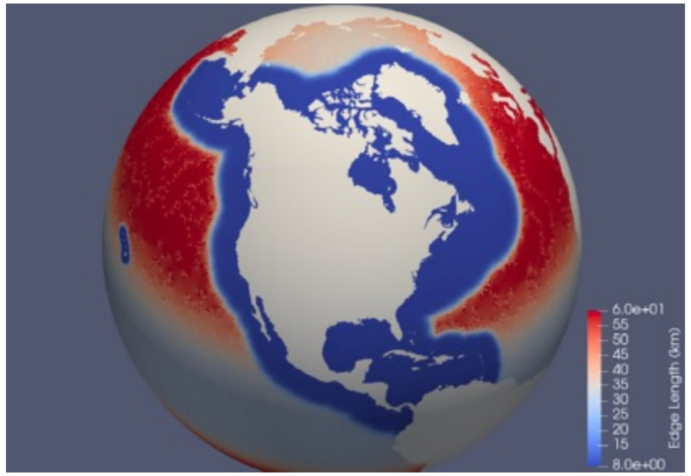
Tropical cyclone frequency and intensity much better simulated at HR



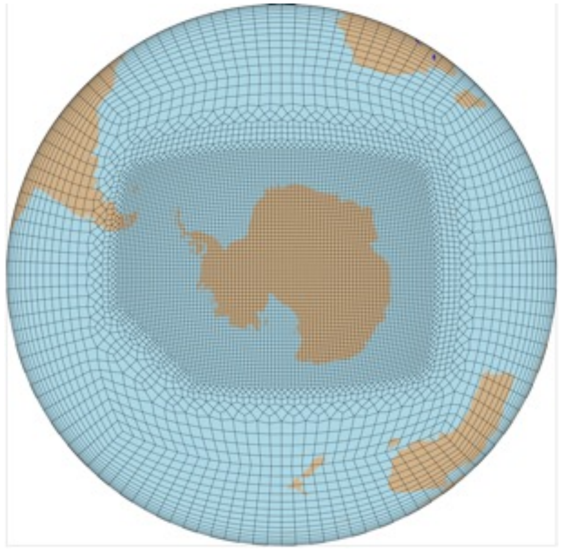
Regional refinement for computational efficiency

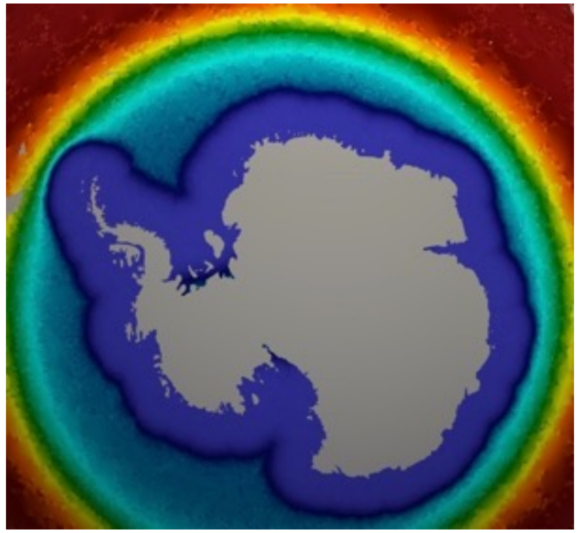
North America RRM

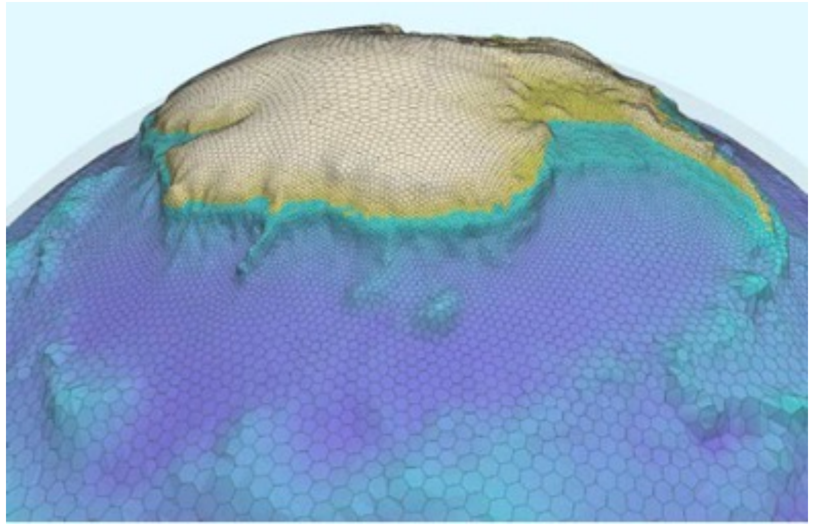




Antarctica RRM



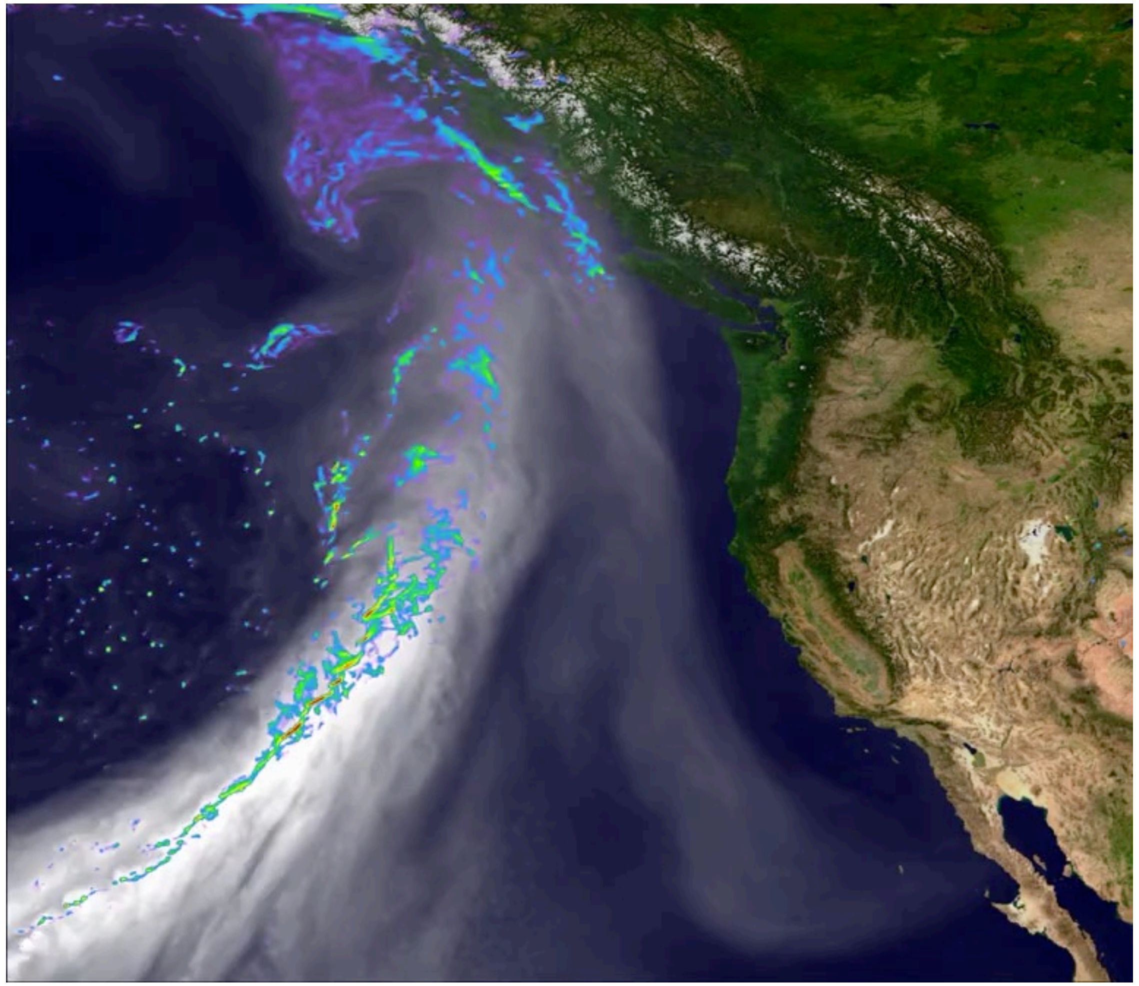




Global storm resolving modeling at 3 km resolution

- Achieved skillful simulations at 3 km resolution without tuning
- C++ version dycore at 1.38 SYPD on Summit: best performance for a global storm resolving dycore with tracers at 3 km resolution
- GPU-enabled version will be operational in November 2021 for exascale computing

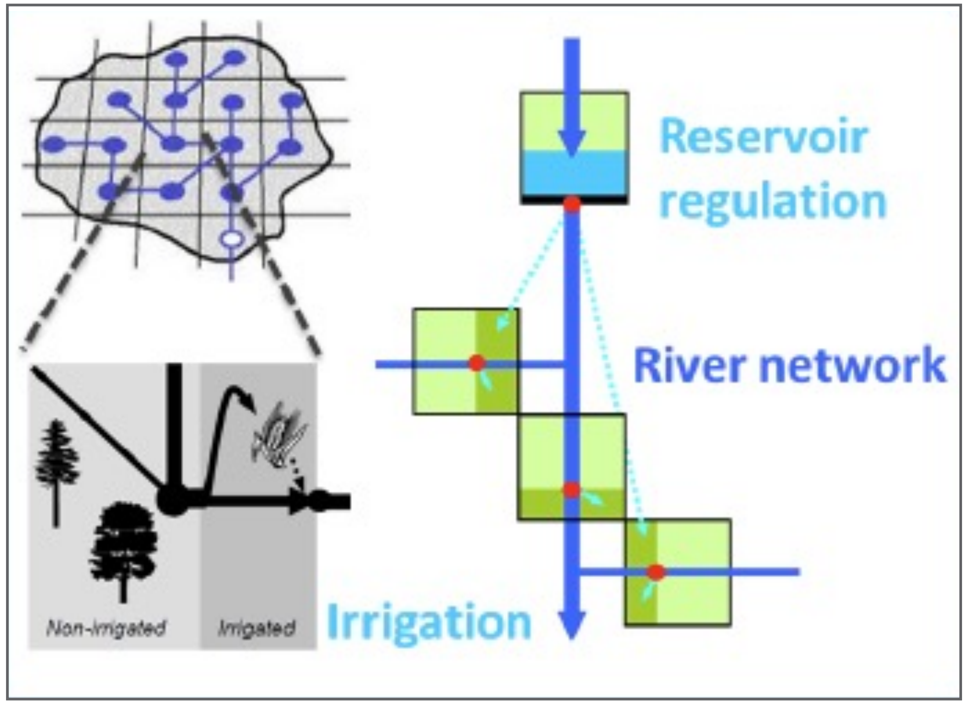
An atmospheric river producing heavy precipitation



(Caldwell et al. 2021 JAMES)

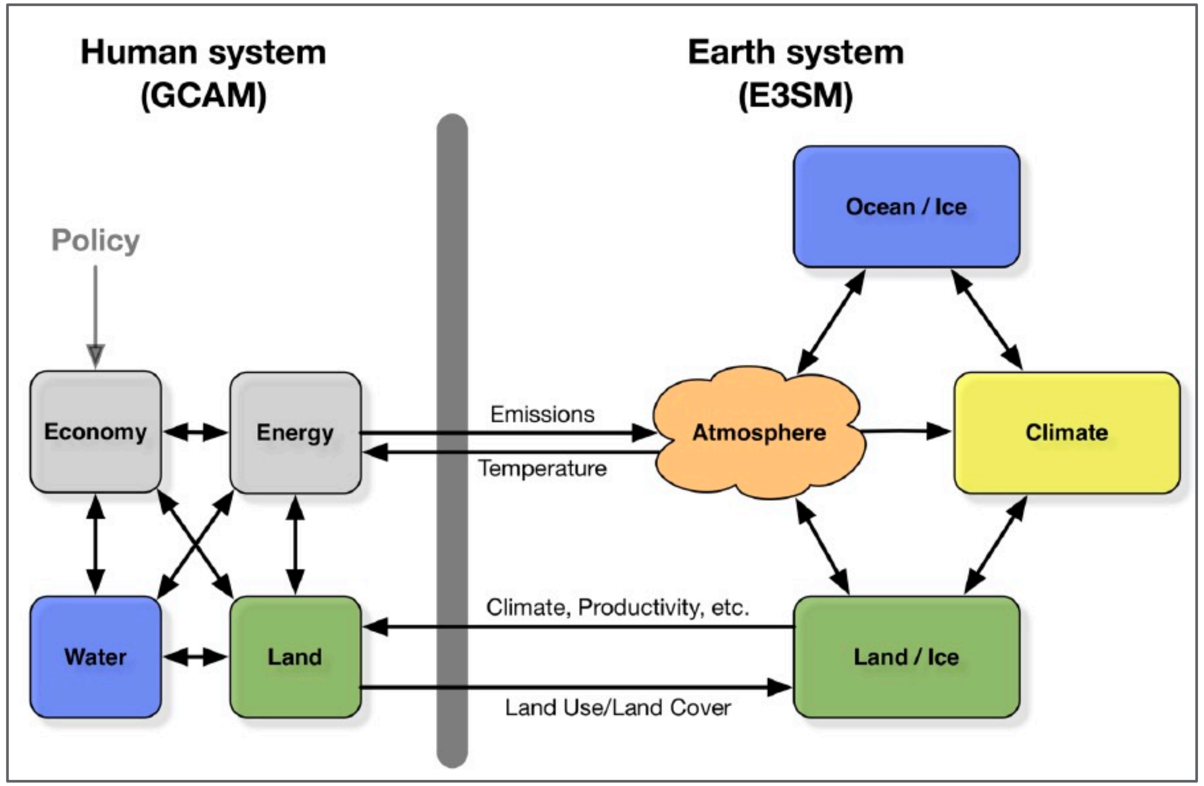
Representing human-earth interactions

Interactions between **land, river, irrigation, and water management** has implications for bioenergy production and water scarcity



(Zhou et al. 2020 JAMES)

Coupling with the Global Change Analysis Model **(GCAM)** to simulate the interactions between the **energy system, water, agriculture and land use, the economy, and the climate**



(Calvin et al.)

Summary

- **Humidity increases nonlinearly with temperature**
  - Extreme weather events correlate more strongly with thetae_sfc
  - As thetae_sfc increases much faster than SAT, so do extreme weather events
  - Implications for warming targets to limit changes in extreme weather events
- **Sharpening of precipitation seasonal cycle in CA**
  - Robust spring/fall drying well understood by physics
  - Uncertainty in winter precipitation due largely to internal variability – irreducible
  - Implications for wildfires, heat extremes, and drought

Summary

- **E3SM supports actionable science:**
  - High resolution modeling and regional refinement
  - Representing human-earth interactions
  - Large ensemble simulations for uncertainty quantification
- **Addresses three science drivers:**
  - Water cycle: water availability, storms
  - Biogeochemistry: heat waves, wildfires
  - Cryosphere: sea level rise, coastal inundation
- **Collaborations between earth and computational scientists:**
  - Optimize performance for DOE computers
  - GPU-enabled modeling for exascale computing
  - Use of ML/AI to improve accuracy and performance (AI4ESP)